LONDON-WEST MIDLANDS ENVIRONMENTAL STATEMENT

Volume 5 | Technical Appendices

CFA25/26 | Castle Bromwich to Curzon Street

Initial groundwater modelling for the Bromford tunnel portals technical report (WR-004-020)

Water resources

November 2013

ES 3.5.2.25-26.2

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Appendix WR-004-020

Environmental topic:	Water resources and flood risk assessment	WR
Appendix name:	Groundwater modelling report	004
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1 Introduction

1.1 Structure of the water resources and flood risk assessment appendices

1.1.1 The water resources and flood risk assessment appendices comprise a number of parts. The first of these is a route-wide appendix (Volume 5: Appendix WR-001-000).

1.1.2 A number of specific appendices for each community forum area are also provided. For the Castle Bromwich and Bromford area (CFA25) and Washwood Heath to Curzon Street area (CFA26) these are:

- water resources assessments (Volume 5: Appendix WR-002-025 and WR-002-026);
- flood risk assessments (Volume 5: Appendix WR-003-025 and WR-003-026)
- a hydraulic modelling report for the River Tame (Volume 5: Appendix WR-004-019);
- a hydraulic modelling report for the River Rea (Volume 5: Appendix WR-004-021); and
- a groundwater modelling report for the Bromford tunnel portals (this appendix).

1.1.3 Maps referred to throughout the water resources and flood risk assessment appendices are contained in the Volume 5 water resources map book.

1.2 Scope of this assessment

1.2.1 Part of the Proposed Scheme within the Castle Bromwich and Bromford area (CFA25) and Washwood Heath to Curzon Street area (CFA26) includes a twin bore tunnel, the Bromford tunnel. As part of the Flood Risk Assessments (Volume 5: Appendices WR-003-025 and WR-003-026) it was identified that the Bromford tunnel and tunnel portals may have an effect on groundwater flood risk. Desk study review indicated a high water table and permeable water bearing deposits within the river valleys along the tunnel alignment. It was recommended that the tunnel pre- and post-construction effects on groundwater levels were investigated further, by developing a local scale numerical groundwater model, to establish the potential impacts and mitigation where necessary.

1.2.2 The purpose of the groundwater modelling exercise is to understand the potential effect on groundwater levels in the vicinity of the Bromford tunnel portals and the 'cut and fill' tunnel entrances which cut through the superficial deposits to the underlying low permeability bedrock. The methodology for constructing and running a local scale 3D groundwater model of the tunnel includes the following steps:

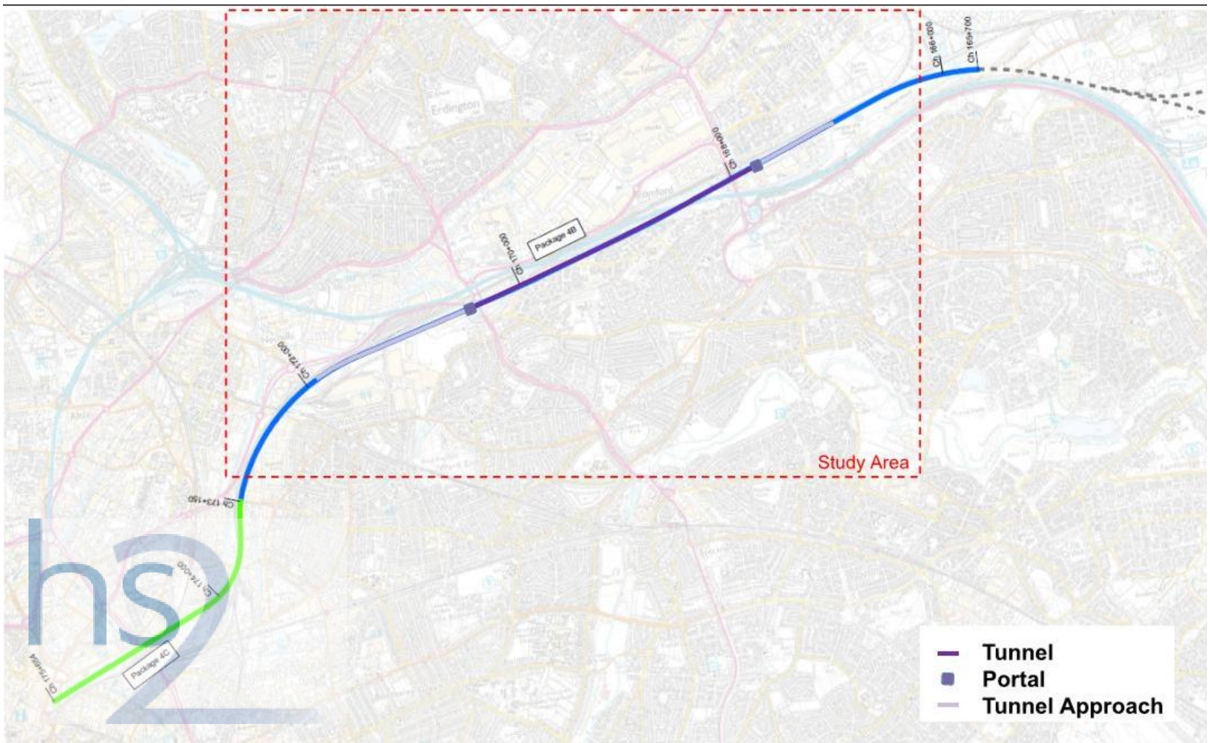
- data collection and review including available geology, climate, hydrology and hydrogeology data sets, as well as the tunnel design and geometry;
- development of a geological and hydrogeological conceptual model of the tunnel and surrounding area;
- construct a calibrated 3D groundwater flow model of the tunnel and the surrounding area using the conceptual model to reflect existing baseline conditions (pre-construction); and,
- use the baseline model to introduce the 'cut and fill' tunnel and tunnel portals to simulate

the potential effects on groundwater (post-construction).

1.3 Location

1.3.1 The Proposed Scheme of the Bromford tunnel and portals is shown in Figure 1. The route of the tunnel generally follows the valley of the River Tame towards central Birmingham.

Figure 1: Tunnel location including portals and 'cut and fill' tunnel approaches



2 Study area

2.1 Proposed scheme

2.1.1 The tunnel is proposed to be a twin bored tunnel, constructed using a TBM, with a 7.55m internal diameter and a length of approximately 2.85km. The top of the tunnel bore will be up to 21m below existing ground level, with the track level up to 27m below ground level.

2.1.2 The Bromford tunnel east portal approach comprises 700m long retained cutting of diaphragm walls, in-situ concrete base and permanent props. The tunnel then passes beneath the A452 Chester Road, the River Tame (three times), the M6 elevated motorway and numerous industrial and residential buildings. The Bromford tunnel west portal consists of 1.4km retained cutting through brownfield industrial sites, again using mainly diaphragm walls, in-situ concrete and permanent props but with short sections of steel sheet piles. The Proposed Scheme drawings are shown in Volume 2: Map book CT-06.

2.2 Topography

2.2.1 The topography of the study area is shown in Figure 2 and Figure 3, including the digital elevation model (DTM), showing ground level at 1m accuracy (maOD).

Figure 2: Topography of the study area

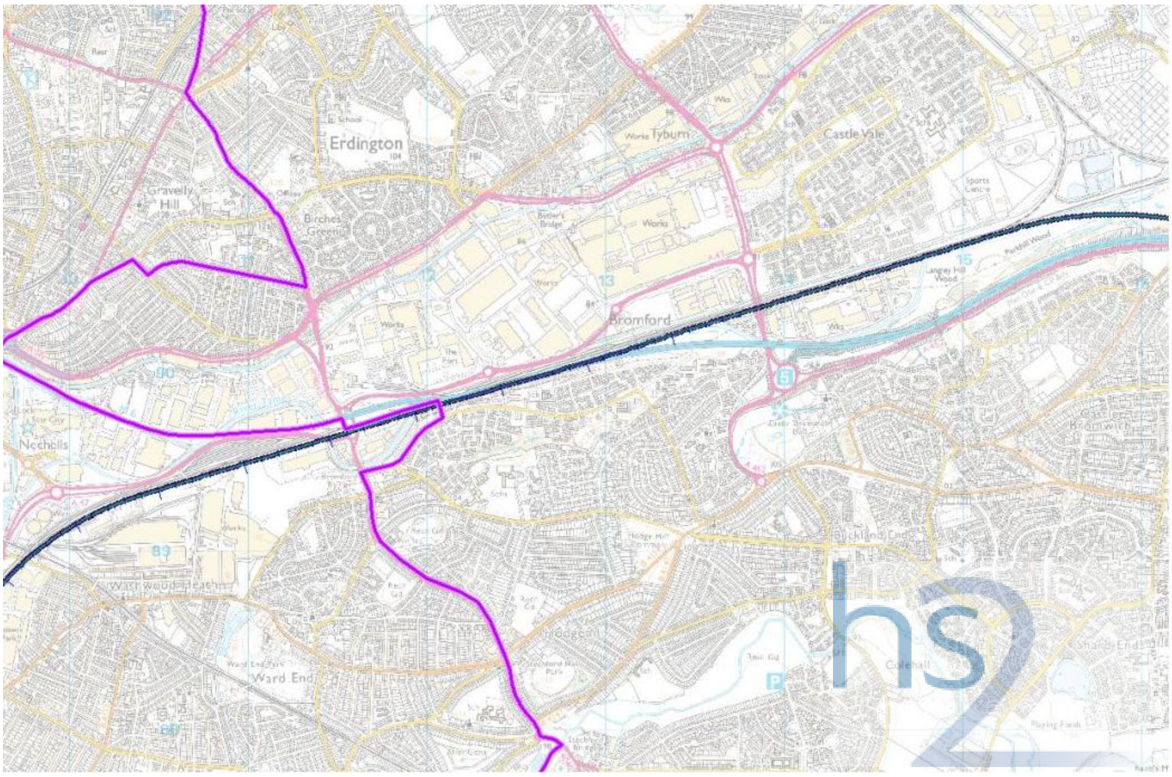
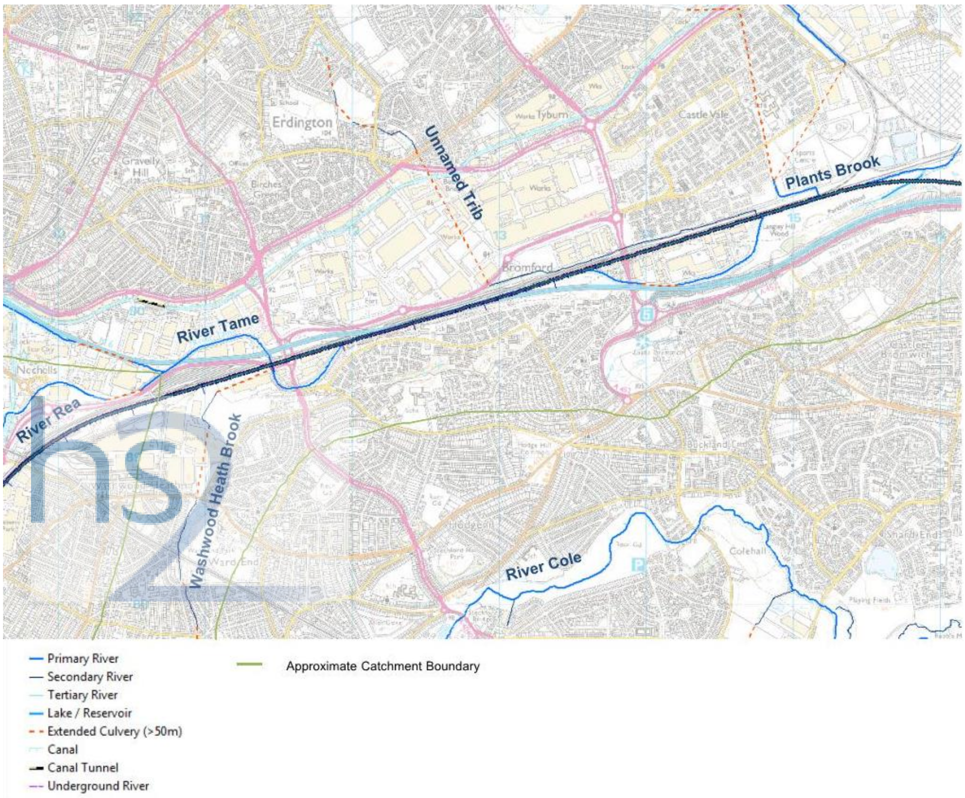


Figure 3: Digital elevation model of the study area

2.2.2 The Tame valley generally has a broad open profile with gently sloping sides, rising 40-50m from the valley bottom. However on the southern valley side east of Bromford there is a steep "cliff" up to 30m high. The valley sides are dissected by several tributary valleys, one of which is occupied by the River Rea as shown in Figure 4. The valley bottom is typically about 1km across and is characterised by river terraces which form localised steps in the topography at their margins.

Figure 4: Rivers and catchment boundary



2.3 Land use

2.3.1 In the west of the study area, near Washwood Heath, the land use is entirely urban, mainly commercial and industrial, but with some residential. However, east of Bromford, the valley bottom and the steep margin to the south becomes semi-rural and forms a nature reserve.

2.4 Geomorphology

2.4.1 The landscape has been affected by the advance of glacial ice on several occasions, followed by a significant period of erosion that has removed much of the material deposited by the glacial phases. The present course of the River Tame in part follows hollows in the landscape eroded by glacial meltwater and is infilled with glacial deposits. The landscape retains the effects of the last (Devensian) glacial period when periglacial conditions prevailed. The River Tame has been diverted to a relatively straight alignment though Park Hall nature reserve, and is canalised under the M6.

2.4.2 The steep cliff on the southern valley side was affected by mass wasting periglacial processes during the last glacial period, forming an apron of Head at its base. This slope, now thickly wooded, was observed to exhibit superficial instability (tilted trees), during a site walkover in July 2012.

2.5 Hydrology

2.5.1 Figure 4 shows the main (primary) rivers, local drainage and topographic catchment boundary.

2.5.2 The River Tame is the most significant watercourse in the West Midlands conurbation and drains a total catchment of 133km^2 before discharging into the River Trent at Alrewas, north east of Lichfield. The majority of the catchment is heavily urbanised and the channel has been extensively modified for a large proportion of its length. The river has a typical width of approximately 15m in the vicinity of the tunnel and depth of approximately 1m.

2.5.3 The nearest Environment Agency river flow gauging station is located at Water Orton (NGR SP1698 9142). The gauging station catchment is described as including an extensive cover of Boulder Clay and glacial sands and gravel , and has a base flow index (BFI, ratio of mean annual base flow to mean total flow) of 0.50. This indicates that groundwater base flow is a reasonable component of total river flow in the Tame upstream of Water Orton gauging station.

2.5.4 Local to the Proposed Scheme, the River Tame flows along the north eastern boundary of the Star City commercial development, it is then joined by the River Rea and flows eastwards through more industrial and commercial areas such as Hurricane Park in a modified but relatively natural channel. The river then loops to the south and flows underneath the M6, the A47 Heartlands Parkway and the Birmingham and Derby Line.

2.5.5 Bromford Lane passes over the river as it begins to loop northwards, it then orientates eastwards and flows under the M6 between the residential area of Bromford to the south and the Birmingham and Derby Line, the A47 Heartland Parkway and an extensive area of industrial development to the north. At this point the channel becomes a very heavily modified two stage concrete channel with the piers supporting the M6 located in the middle of the channel. The motorway veers south away from the river after approximately 1km but the river and motorway converge at Chester Road near Castle Bromwich Business Park and the river is once more located under the M6 viaduct downstream of Chester Road for a short length. The Tame then flows north and east in an embanked channel adjacent to Langley Hill and Parkhill Woods.

2.6 Rainfall and climate

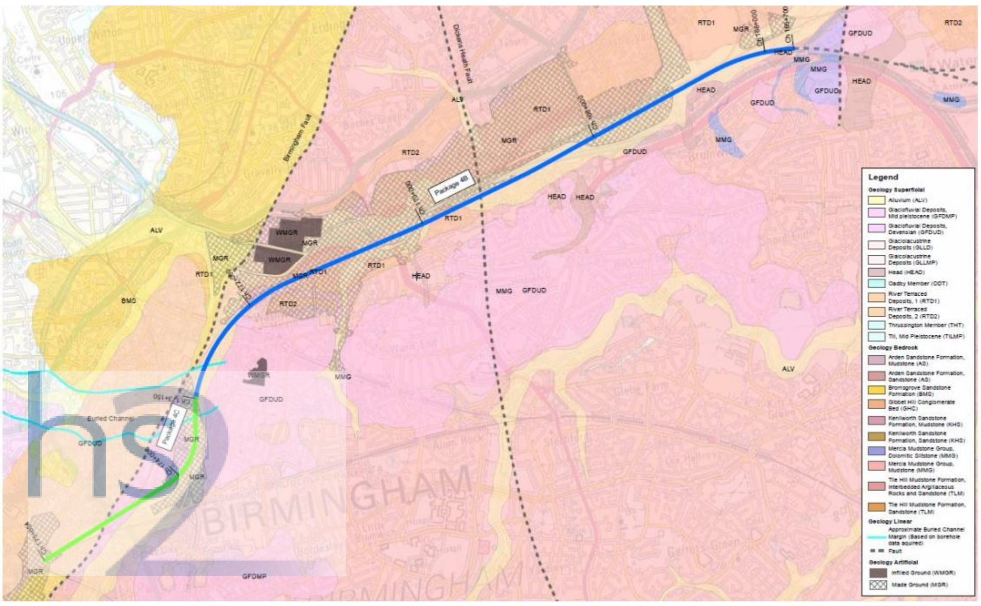
2.6.1 The nearest Environment Agency rainfall gauge is at Saltley (NGR SP 0915 8801) which has a record from 2001 – 2013, during which time the long term average annual rainfall has been 714 mm/year.

2.6.2 The Bromford tunnel is within the buffer zone of the Environment Agency regional groundwater model for the Lichfield Permo-Triassic Sandstone. This groundwater model has processed rainfall and evaporation data for the area to generate effective rainfall. The Litchfield model long term average annual rainfall (1962 – 2011) is 712mm/year, which is comparable to the rainfall at the Saltley gauge. The model has also calculated the long term average annual potential evapotranspiration (1970 – 2011) of 486mm/year. The long term annual effective rainfall is therefore approximately 226mm/year.

2.7 Geology

2.7.1 The solid and superficial geology of the route corridor is shown in Figure 5 and has been informed by the geotechnical desk studies and review of BGS borehole records.

Figure 5: Solid and Superficial Geology



Solid geology

2.7.2 The geological structure within the study area comprises Triassic deposits (Mercia Mudstone Group), forming part of the Knowle Basin, overlain by glacial and alluvial superficial deposits.

2.7.3 At the A4540 Lawley Middleway, beyond the extent of the study area, the Proposed Scheme crosses the line of the Birmingham Fault which trends southwest – northeast. This fault exposes the Triassic Sherwood Sandstone Group, Bromsgrove Sandstone Formation to the west of the fault.

Mercia mudstone

2.7.4 The Mercia Mudstone comprises a thick sequence of red brown mudstones deposited in an arid continental alluvial and lacustrine floodplain. The Mercia Mudstone of the Knowle depositional basin have an overall thickness of some 350 – 400m, the section traversed by the proposed tunnel is towards the base of the sequence, and belongs to the Sidmouth Mudstone Formation.

2.7.5 The thickness of Mercia Mudstone strata varies from about 25m, just east of the Birmingham Fault at Saltley to about 60m at the Dickens Heath Fault, reflecting a continuing very gentle south east dip. The Dickens Heath Fault down faults the base of the Mercia Mudstone to the east by about 80m, so that its thickness to the east of the fault is 140 – 160m. To the west of the Dickens Heath Fault, the top of the underlying Sherwood Sandstone is some 40m below the tunnel invert, to the east of the fault this increases to 120m.

2.7.6 The Mercia Mudstone typically occurs as a weak red brown silty mudstone with minor amount of carbonate (dolomite) and gypsum when unweathered. The Mercia Mudstone typically weathers by the dissolution of the carbonate and gypsum component to stiff friable silty clay. This weathered zone is often diffuse, and may be 10m or more thick. Occasional beds of dolomitic siltstone (skerries) occur within the Mercia Mudstone, these beds are generally thin (0.1 - 1.0m), but when unweathered are medium strong rocks. Several sandstone horizons are present on the southern side of the Tame Valley east of Langley Hill Woods, and are probably partly responsible for the steep topographic feature in this area.

2.7.7 It is noted that the siltstone / sandstone bands have higher mass permeabilities than the mudstones and may act as pathways for groundwater flow (BGS, 2002)[1]. The siltstone / sandstone bands are reported in the 2011 GEL boreholes, and some of the Heartlands Spine Road boreholes , but they occur sporadically. Elsewhere in the Mercia Mudstone sequence, the thin siltstone / sandstone bands, can be laterally persistent, and it is possible that the siltstone/sandstone bands that may intersect the tunnel will be laterally persistent.

[1] British Geological Society, (2002)

2.7.8 The Dickens Heath Fault will cross the tunnel alignment at Hodge Hill. A narrow zone of fault disturbed and weathered material may be present. This weathered zone may have a higher permeability and might contain groundwater. Overall intact unweathered Mercia Mudstone has low permeability of 10-9 to 10-11 (BGS 2002), however this can increase within the weathered zone to, due to an increased frequency of fracturing.

2.7.9 The 2011 Geotechnical Engineering Boreholes and the 1991/94 Heartlands Spine Road Boreholes indicate that the weathered zone is generally between 5.0 and 10m thick. It is noted however, that the thickness of the weathered zone varies in an irregular fashion in the 2011 GEL boreholes and the 1991 /1994 Heartlands Spine Road Boreholes.. Close to the western portal the weathering zone is 10 – 15m thick.

Superficial geology

2.7.10 The superficial deposits overlying the Mercia Mudstone in the study area are shown in Figure 5 and include:

- alluvial deposits;
- River Terrace deposits; and
- glacial deposits.

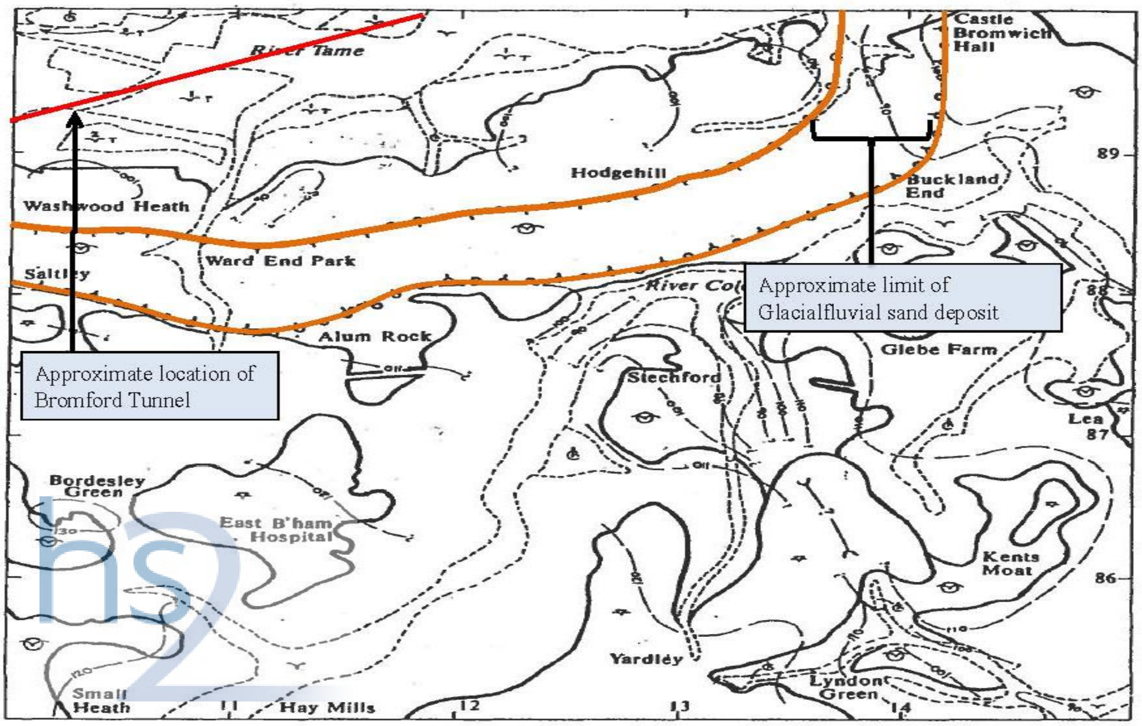
2.7.11 The River Rea, which is to the west of the Bromford tunnel west portal, joins with the River Tame, shows Alluvial Deposits, laid down by the Rivers Rea and the River Tame since the end of the last (Devensian) glacial period, generally comprise clayey silts, sand and gravel and can be up to 5m thick, typically 3 – 4m. In many places the alluvial material has been disturbed by the construction of mills, flood defences, and urban development, and merges into an extensive spread of Made Ground reflecting human activities.

2.7.12 Along the valley bottom of the River Tame, there are a well-developed series of River Terrace Deposits. The younger and more extensive deposit – the First Terrace – was formed during the last glacial period when the Devensian Ice Sheet encroached into the catchment of the River Tame in the Walsall area and is comprised of a sand and gravel layer that is generally 4– 5m thick. This was originally 1–3m above the present day alluvial flood plain, but this relationship is largely obscured by urban development and filling across the valley bottom.

2.7.13 The older Second Terrace (Hams Hall Terrace) occurs as a semi-continuous feature along the lower part of the valley side, particularly on the north side. It generally occurs about 7m – 9m above the present day flood plain, but the elevation is variable, and there may be more than one age of material. It comprises a clayey sand and gravel, generally 2m – 4m thick, which is extensively cryoturbated in places.

2.7.14 The superficial glacial deposits form a discontinuous covering to the Triassic deposits across the upper parts of the Rivers Rea and Tame valley sides. These deposits probably reflect several phases of glaciation between about 400,000 and 200,000 years ago. Due to erosion by the Rivers Rea and Tame after the last glacial phase, the cover of glacial material is now discontinuous. They also occur within linear hollows eroded into the Triassic strata, by sub-glacial melt water during a previous glacial period. Figure 6 shows the approximate location of a fluvio-glacial channel which follows the current topographic divide between the River Tame and River Cole, eventually joining the Tame near Castle Bromwich Hall. These fluvio-glacial deposits are described as sand and gravel with a thickness of up to 20m in places. These deposits form a palaeo-channel running along the catchment boundary between the River Tame and the River Cole. BGS borehole logs indicate the presence of this channel

Figure 6: Glaciofluvial channel parallel to Tame Valley (C08/006-CCSL British Geological Survey © NERC. All rights reserved)



2.7.15 Significant areas of Made Ground are present, relating to past human activities. Much of this Made Ground has been placed across the valley bottoms of the Rivers Tame and Rea to provide development platforms above flood levels for industrial land use, and as embankments for main line railways and extensive railway sidings. Some of this Made Ground is a consequence of the long and intensive industrial land use of the area.

2.8 Hydrogeology

2.8.1 The strata within the study area have been classified using the Environment Agency aquifer classification framework and are summarised in Table 1Table 1 and their distribution shown in Figure 7 and Figure 8. The model assumes that groundwater flow is through the superficial deposits based on borehole logs and in terms of groundwater flooding. From the available data there is not enough information to incorporate this into the model. Further ground investigation would be needed to determine if the Arden Sandstone is present within the area.

Table 1: Summary of aquifer designations for geological units

Geological unit	Aquifer designation	Typical hydraulic conductivity (m/s)	Source
Alluvium	Secondary A	1x10-9 – 1x10-5	Domenico and Schwartz, 1998
River Terrace Deposits	Secondary A	3x10-4 – 1x10-6 (sands and gravels)	Domenico and Schwartz, 1998
Glaciofluvial Deposits	Secondary A	3x10-4 – 1x10-6 (sands and gravels)	Domenico and Schwartz, 1998
Mercia Mudstone	Secondary B	1x10-11 – 1x10-8	Domenico and Schwartz, 1998

Figure 7: Aquifer designations (Solid)

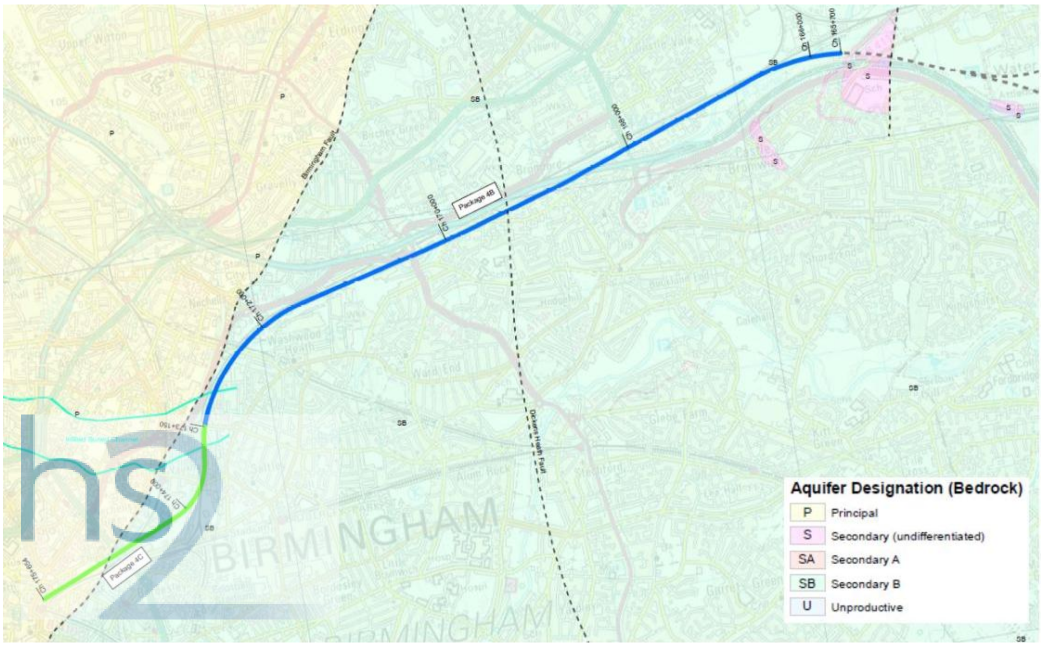
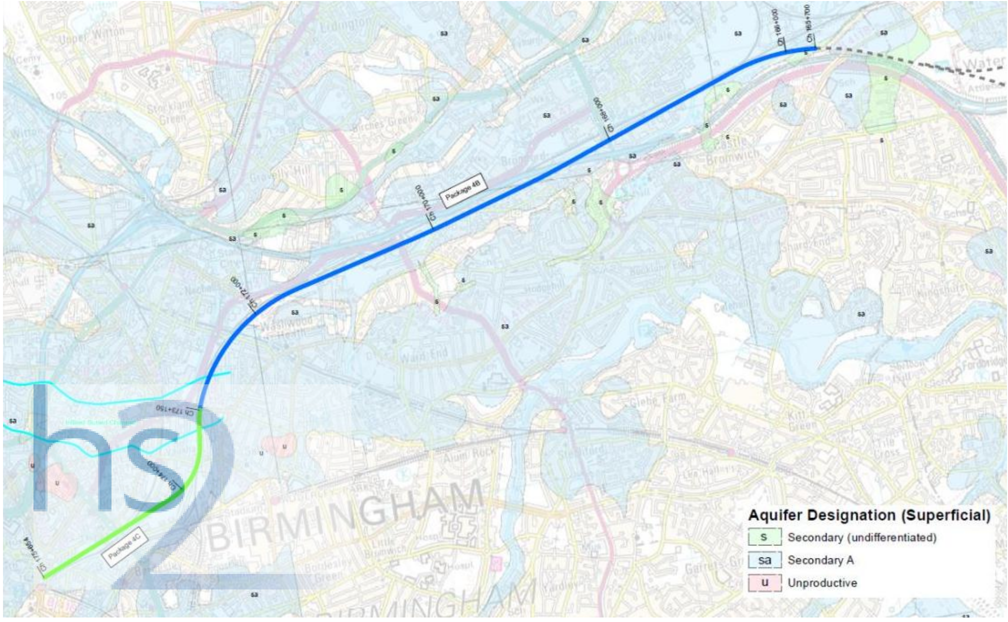


Figure 8: Aquifer designations (Superficial)



2.8.2 The superficial deposits (Alluvium, River Terrance Deposits and Glaciofluvial Deposits) are all Secondary A aquifers, which are generally considered to consist of variable permeability layers capable of supporting water supplies at a local scale.

2.8.3 The Mercia Mudstone is a Secondary B aquifer, which are generally of lower permeability and may locally store groundwater due to localised features such as thin fissures, thin permeable horizons and weathering.

2.8.4 There is no site specific information on aquifer properties. Typical literature values for hydraulic conductivity are presented in Table 1.

Groundwater levels and flow

2.8.5 There are no dedicated groundwater monitoring data points within the study area (e.g. there are no Environment Agency groundwater level monitoring boreholes) and information on groundwater levels has been obtained from water level strike observations within existing borehole logs available from the BGS. These indicate that groundwater in the valley bottom within the superficial deposits is approximately 2 to 6m below ground level. It appears that shallow groundwater flow generally follows the topography draining the valley sides towards the River Tame.

2.8.6 There is a spring and drainage shown on the 1:10,000 scale OS map at Hodge Hill, which is on the southern valley side in the area of the River Terrace Deposits and Glacio-fluvio deposits further up the valley side. This may indicate groundwater flow and discharge to the north from these deposits. Similarly, in the area of Castle Bromwich Hall on the southern valley side of the Tame, there is an area of drainage corresponding to the assumed position of the glacio-fluvial deposits, and may indicate some groundwater through flow from this feature.

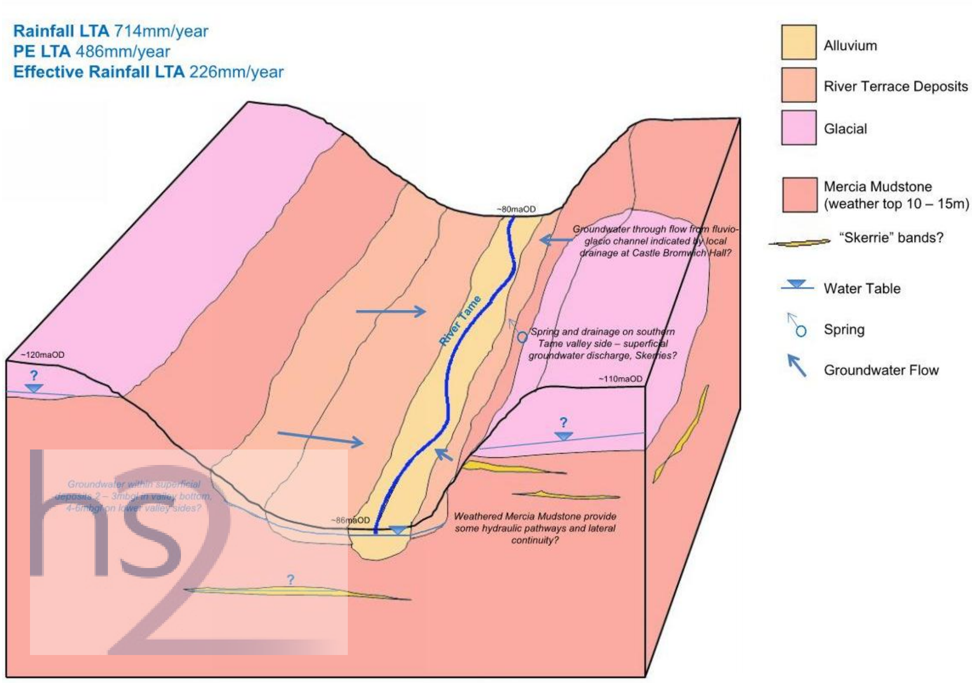
2.8.7 Groundwater may be encountered within the Mercia Mudstone, either within the weathered upper section or within siltstone / sandstone "skerrie" bands where present. It is thought that the steep cliff on the southern valley side may be related to the presence of harder siltstone and sandstone bands.

2.8.8 There are no licenced groundwater abstractions within the study area, suggesting that the superficial deposits are not used for water supply purposes.

3 Conceptual model

3.1.1 The hydrogeological conceptual model of the local area is shown in Figure 9 and key components summarised in the following sections.

Figure 9: Hydrogeological conceptual model



3.2 Geological conceptual model

3.2.1 The superficial deposits have been categorised into the following strata and associated thicknesses based on BGS borehole records and 1:10,000 superficial geology map.

- 1st River Terrace deposits, up to 3m thick;
- 2nd River Terrace deposits, up to 4m thick;
- Glaciofluvial deposits, ranging between 4m – 15m thick; and
- Alluvium, up to 6m thick.

3.2.2 All of these deposits are generally described as being free draining sands and gravels.

3.2.3 The underlying bedrock of the Mercia Mudstone is expected to be weathered in its upper 10 – 15m, the glacial and alluvial materials deposited and infilling hollows within the bedrock. Siltstone and sandstone "skerrie" bands occur in places and are thought to occur on the southern side of the Tame valley in the area of the steep "cliff".

3.3 Hydrogeological conceptual model

3.3.1 The glacial and fluvial superficial deposits are all considered Secondary A aquifers and generally described as sand and gravel materials which are considered permeable (permeability 1x10-6m/s).

3.3.2 The underlying Mercia Mudstone is a Secondary B aquifer, although generally much less permeable than the overlying superficial deposits (permeability 1x10-9m/s). The Mercia Mudstone is expected to be weathered in its upper 10 – 15m and include more permeable siltstone/sandstone "skerrie" bands in places which can be water bearing.

3.3.3 Groundwater within the valley bottom is expected to be shallow adjacent to the river, 1 – 3m below ground level, and at greater depth on the valley sides. Groundwater flow within the superficial deposits is expected to follow the topography. Springs and density of local drainage on the southern valley side may indicate shallow groundwater flow to the north into the Tame valley from the River Terrace and Glacio-fluvio deposits and possibly "skerrie" bands.

3.3.4 The long term average rainfall for the area is approximately 714mm/year, potential evaporation approximately 486, meaning an effective rainfall of approximately 226mm/year. The largely urban catchment with areas of hard standing would mean that there will be a significant component of run-off with less than 50% of effective rainfall available as infiltration recharge. Within an urban area the spatial and temporally variable effects of type and extent of impermeable cover, drainage systems and management, mains / sewer leakage conditions makes assessment of the groundwater recharge component uncertain.

3.3.5 The River Tame is the main drainage feature, which is embanked and a modified channel in places, but is assumed to generally be in continuity with groundwater. Some parts of the river in this area are in concrete channel. The Environment Agency gauging station downstream at Water Orton has a BFI of 0.50.

4 Numerical model design

4.1.1 Numerical groundwater modelling has been carried out using MODFLOW, which is an industry standard groundwater modelling code developed as freeware by the United States Geological Survey (USGS). MODFLOW is a 3D finite difference software package for analysing groundwater flow within porous materials such as soil and rock, which can model both saturated and unsaturated flow and processes such as the infiltration of precipitation. Visual MODFLOW Pro 2011.1 is a graphical user interface and post-processing package developed by Schlumberger Water Services which has been used to build and run the MODFLOW model.

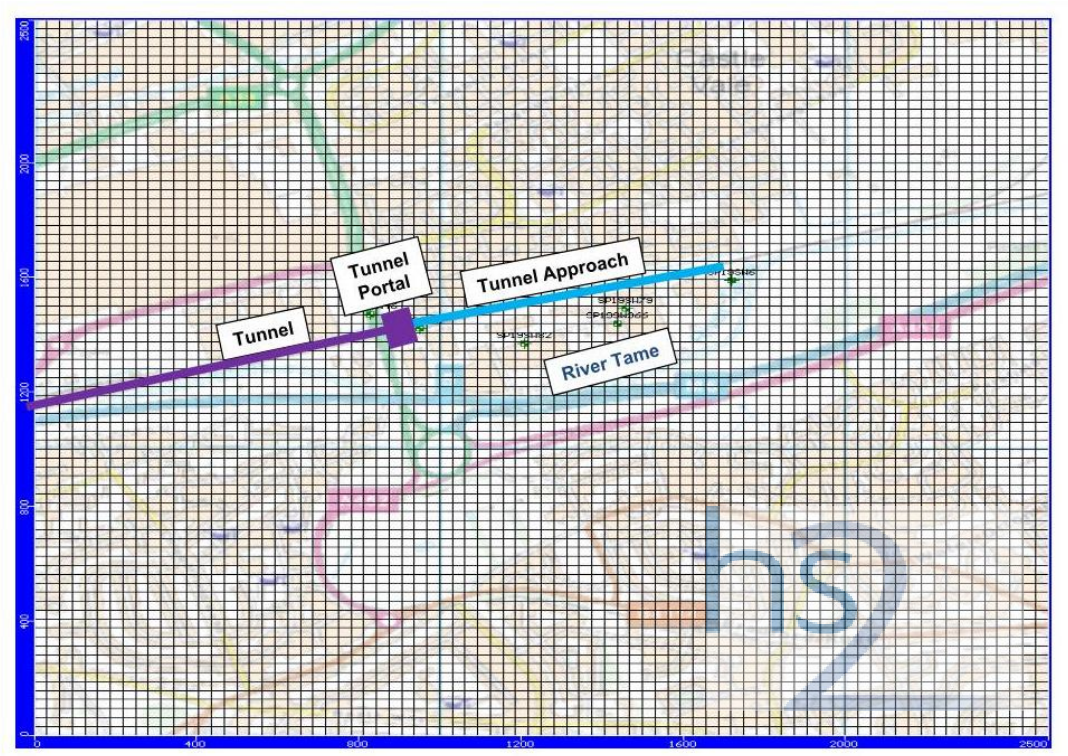
4.1.2 Two local scale groundwater models were developed, one for each portal, the design, build and calibration of each of these are described separately in the following sections.

4.2 Bromford tunnel east portal

Grid design

4.2.2 The model domain consists of a roughly rectangular area set at an angle following the valley of the River Tame (Figure 10). The model domain was set as an area of 2.5km (north to south) by 2.5km (east to west). The finite difference grid is discretized into columns of 30m (north to south) and rows of 30m (east to west).

Figure 10: Bromford tunnel east portal model – model grid and model domain

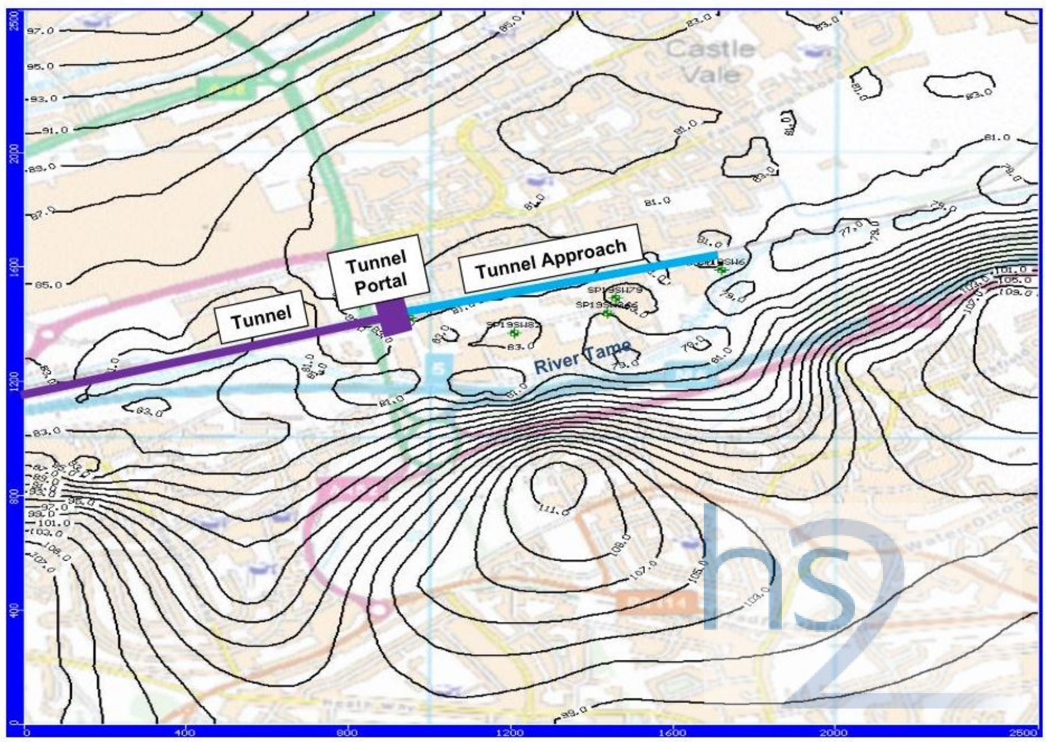


4.3 Layers and surfaces

4.3.1 The highest point of the model lies on the northern boundary of the model which form on the side of the Tame river valley. The ground elevation falls from a maximum of 88mAOD on the northern boundary to a low of 78mAOD along the River Tame which forms the southern boundary.

4.3.2 The ground surface elevation has been obtained from available 1m resolution DTM data as well as by digitization of Ordinance Survey contour maps and spot heights. The ground surface points and elevations were then gridded and interpolated (using Kriging) within Visual MODFLOW to create the ground surface from which the model layers were interpreted from. The model surface elevation is shown as Figure 11.

Figure 11: Bromford tunnel east portal model – digital surface elevation (mAOD)



4.3.3 The distribution of surface geology in the area of the Bromford tunnel east portal is shown as Figure 12. Two model layers have been created to represent the strata present in the study area and are summarised in Table 2.

Figure 12: Bromford tunnel east portal model – superficial geology and observation points

Table 2: Eastern Portal model layer designation

Model layer	Name	Hydrogeological unit	Layer thickness
1	Superficial deposits	A mixture of alluvium and river terrace deposits. All designated as Secondary A aquifers. Layer also includes areas of made ground.	Based on borehole data the thicknesses of the superficial deposits have been assigned as follows: Alluvium: 5-7m 1st River Terrace deposits: 4-5m
2	Mercia Mudstone	Generally assumed a non-aquifer, EA designation of Secondary B.	The layer thickness of the Mercia Mudstone has been set at an elevation of 30mOD. Approximate thickness ranges from 30m to 50m within the model.

4.3.4 MODFLOW type 3 layers (variable confined/unconfined variable transmissivity type) were used throughout.

Head observation wells

4.3.5 There are no groundwater monitoring wells within the model domain, including no Environment Agency groundwater level monitoring boreholes. All water level data has been taken from the available BGS borehole logs where water level strike data has been recorded. The location of observation points used in the model for calibration purposes are shown in Figure 12. Most groundwater observation points are located around the tunnel portals within the valley bottom and the model has been calibrated using these points (6 wells in total) as well as the fit to the general conceptual understanding of groundwater flow direction and water level depth.

Boundary conditions

4.3.6 Boundary conditions have been set based on the available geological and hydrogeological information and are shown in Figure 13 and summarised in Table 3.

Figure 13: Bromford tunnel east portal model – model boundary conditions

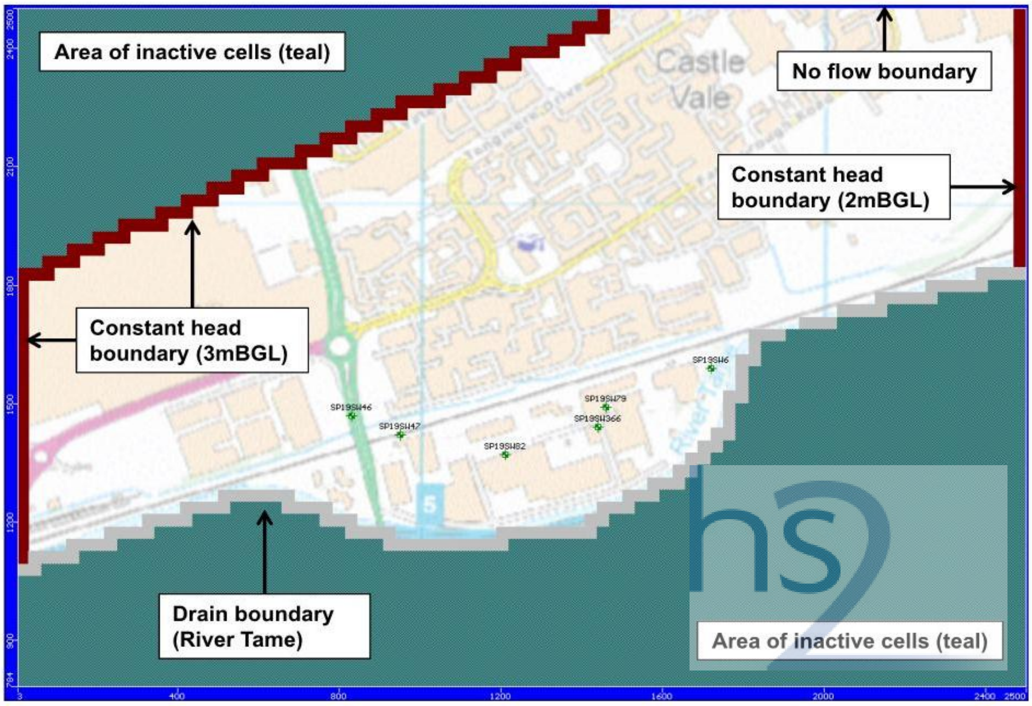


Table 3: Bromford tunnel east portal model boundary conditions

Boundary type	Boundary condition	Justification
No Flow	One 'no flow' boundary was set on the north east border of the model	'No Flow' boundaries have been set on the northeast boundary following the extent of the 1st River Terrace deposits as shown in Figure 2.
Drain	Set from an elevation of 85mOD to an elevation of 76mOD with a conductance of 50m^2/day	The River Tame has been digitized as a fully draining drain boundary. The elevations of the River Tame were assigned from Environment Agency river bed level data.
Eastern boundary constant head	Set at 2m below the ground surface	The eastern boundary of the model has been set as a constant head boundary 2mBGL based off of model calibration and from the available water strike data from BGS boreholes.
Western boundary constant head	Set at 3m below the ground surface	The western boundary of the model has been set as a constant head boundary 3mBGL based off of model calibration and from the available water strike data from BGS boreholes.
Northwest boundary constant head	Set at 3m below the ground surface	The northwest boundary of the model has been set as a constant head boundary 3mBGL based off of model calibration and from the available water strike data from BGS boreholes.
Recharge	Set as 65mm/year over the full extent of layer 1	A recharge value of 65mm/year (approximately 20% of estimated effective annual rainfall) was applied to the entire model domain within the superficial deposits.

Material properties

4.3.7 The hydraulic conductivities used in the final model run are shown in Table 4.

Table 4: Eastern Portal model material properties

Unit	Designation	Hydraulic conductivity (m/s)	Source
Alluvium	Zone 2	Kx = 9x10-4 Ky = 9x10-4 Kz = 9x10-4	Estimate based on typical literature values – then calibrated
River Terrace deposits	Zone 1	Kx = 5x10-4 Ky = 5x10-4 Kz = 5x10-4	Estimate based on typical literature values – then calibrated
Mercia Mudstone	Zone 3	Kx = 1x10-7 Ky = 1x10-7 Kz = 1x10-7	Estimate based on typical literature values – then calibrated

4.3.8 These values are a result of a significant amount of calibration and sensitivity testing. A wide range of conductivities were explored. For modelling purposes, it is assumed that these values represent the bulk hydraulic conductivity for each aquifer unit and are assigned to zones within the model layers representing these geological and hydrogeological units. For this model, hydraulic conductivity of each unit was assumed the same in each direction as the model was not sensitive to isotropy within the different zones.

4.3.9 To achieve a model calibration the Mercia Mudstone and Superficial Deposits were at the more permeable end of expected literature values. It is recommended that further site specific data is collected to confirm the local aquifer properties.

4.3.10 No specific yield or storativity values are required in steady state analyses.

Model run settings

4.3.11 The model scenarios were all run in steady state, meaning that all boundary conditions remained constant and did not vary with time.

Simulation and stress period

4.3.12 It has been assumed that groundwater conditions are in steady state. The steady state simulation of groundwater flows has been carried out over a stress period of 1 year (365 days).

Solver

4.3.13 The solver used for the analysis was Waterloo Hydrogeologic Software, WHS.

Measurement units

4.3.14 The following measurement units are used throughout the simulations:

- length = metres (m);
- time = day (d);
- hydraulic Conductivity = m/s; and
- recharge = mm/yr.

Calibration and sensitivity analysis

4.3.15 Calibration of the Bromford tunnel east portal model was achieved by means of a systematic adjustment of model properties and boundary conditions to achieve the best fit with observation points and the conceptual understanding of groundwater heads and flows. The baseline model calibration statistics for the 6 observation points are summarised in Table 5. These show simulated groundwater level is approximately 2.8m different to the strike data, but this is particularly biased by one of the 6 points being over 5m out. The overall fit and direction of groundwater level contours matched the conceptual model.

Table 5: Model statistics from final calibration

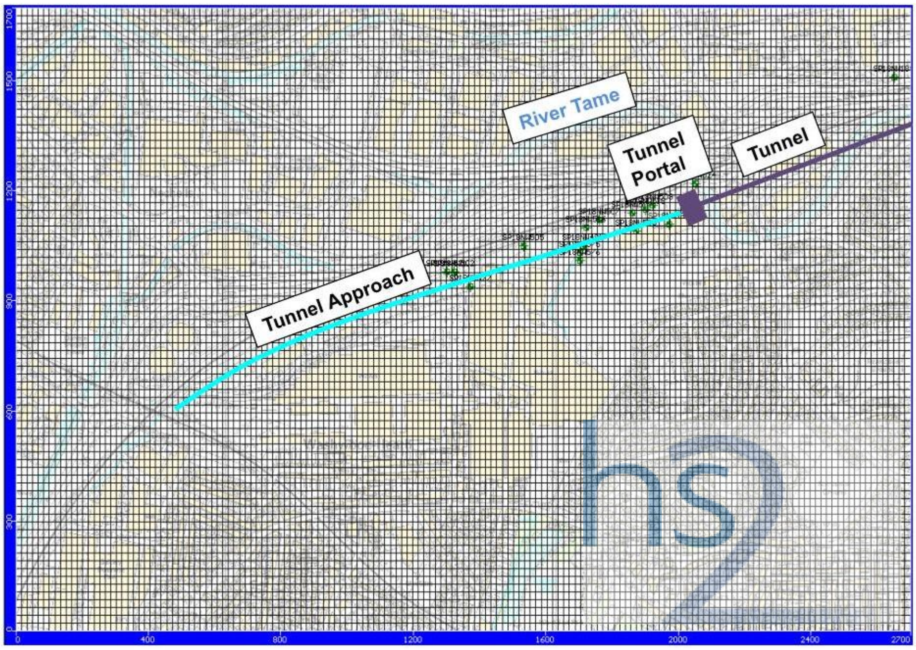
Maximum residual (m)	Minimum residual (m)	Residual mean (m)	Absolute residual mean (m)	Standard error of the estimate (m)	Root mean squared (m)	Normalized root mean squared (%)	Correlation coefficient
-5.18 at SP19SW82	0.832 at SP19SW366	-2.839	3.116	0.956	3.554	56.414	-0.091

4.4 Bromford tunnel west portal

Grid design

4.4.2 The model domain consists of a roughly square area set at an angle following the valley of the River Tame (Figure 14). The model domain was set as an area of 1.7km (north to south) by 2.7km (east to west). The finite difference grid is discretised into columns of 20m (north to south) and rows of 20m (east to west).

Figure 14: Bromford tunnel west portal - model grid and model domain

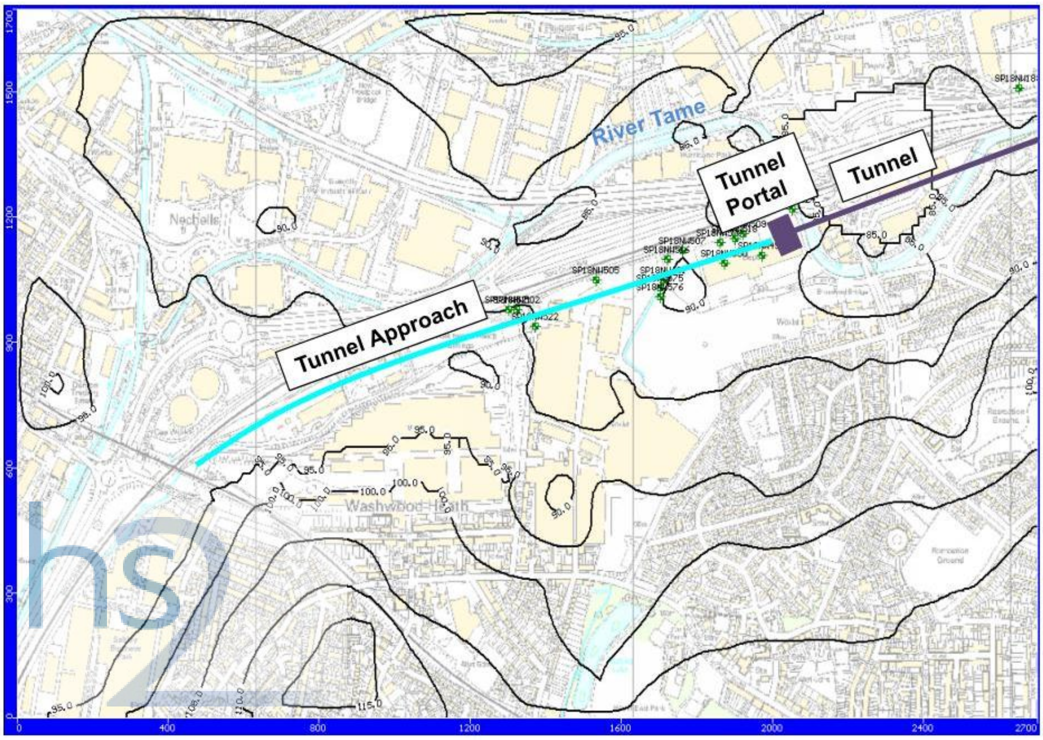


Layers and surfaces

4.4.3 The northern and southern boundaries follow the approximate extent of River Terrace Deposits within the Tame Valley. The northern boundary is set at 90mOD and the southern boundary at 100mAOD allowing for some inflow from the south in the area of the Washwood Heath Brook.

4.4.4 The ground surface elevation has been obtained from available 1m resolution DTM data as well as by digitization of Ordinance Survey contour maps and spot heights. The ground surface points and elevations were then gridded and interpolated (using Kriging) within Visual MODFLOW to create the ground surface from which the model layers were interpreted from. The model surface elevation is shown as Figure 15.

Figure 15: Bromford tunnel west portal model – digital surface elevation (mAOD)



4.4.5 The distribution of surface geology in the area of the Bromford tunnel west portal is shown as Figure 16. Two model layers have been created to represent the strata present in the study area and are summarised in Table 6.

Figure 16: Bromford tunnel west portal - superficial geology and observation points

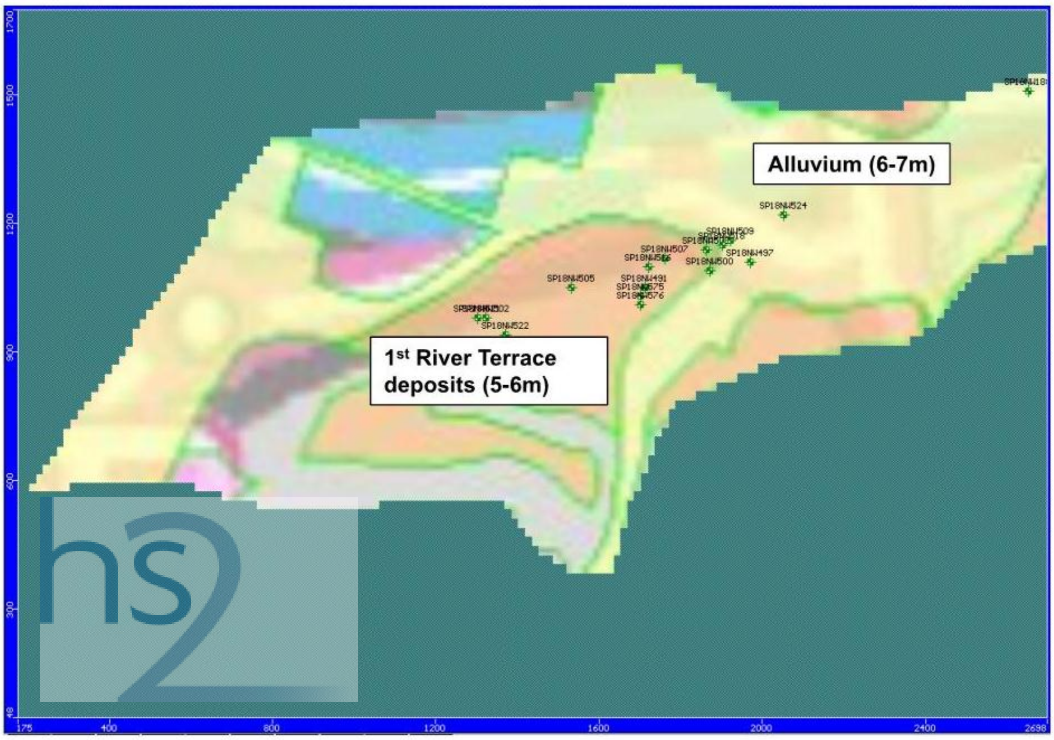


Table 6: Model layer designation

Model layer	Name	Hydrogeological unit	Layer thickness
1	Superficial deposits	A mixture of alluvium and river terrace deposits. All designated as Secondary A aquifers. Layer also has a substantial amount of made ground.	Based on borehole data the thicknesses of the superficial deposits have been assigned as follows: Alluvium: 6-7m 1st River Terrace deposits: 5-6m
2	Mercia Mudstone	Generally assumed a non-aquifer, EA designation of Secondary B. There may be some water bearing "skerrie" bands in the area as indicated by the "cliff" on the south side of the Tame Valley.	The layer thickness of the Mercia Mudstone has been set at an elevation of 30mOD. Approximate thickness ranges from 40m to 55m within the model.

4.4.6 MODFLOW type 3 layers (variable confined/unconfined variable transmissivity type) were used throughout.

Head observation wells

4.4.7 There are no groundwater monitoring wells within the model domain, including no Environment Agency groundwater level monitoring boreholes. All water level data has been taken from the available BGS borehole logs where water level strike data has been recorded. The location of observation points used in the model for calibration purposes are shown in Figure 16. Most groundwater observation points are located around the tunnel portals and the model has been calibrated on these wells (16 wells in total), as well as some general groundwater contours which indicate flow towards the River Tame in the Washwood Heath area.

Boundary conditions

4.4.8 Boundary conditions have been set based on the available geological and hydrogeological information and are shown in Figure 17 and summarised in Table 7.

Figure 17: Bromford tunnel west portal model - model boundary conditions

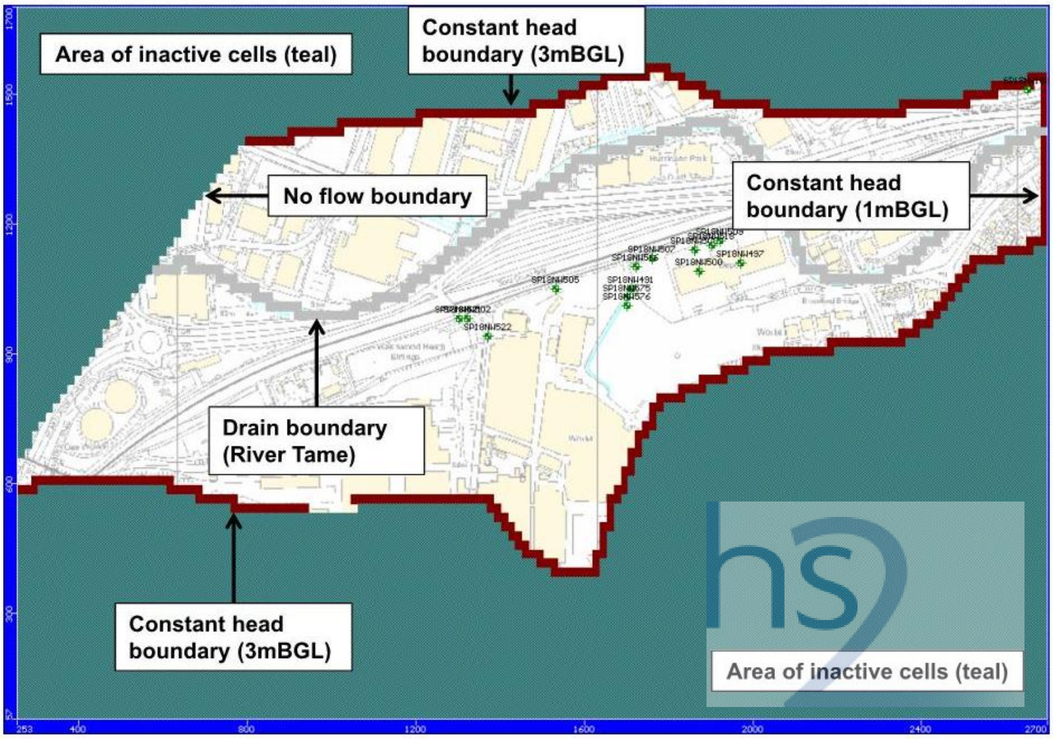


Table 7: Bromford tunnel west portal model boundary conditions

Boundary type	Boundary condition	Justification
No Flow	Set along the western boundary of the model.	'No Flow' boundaries have been set on the western boundary as groundwater contours have shown the majority of flow coming from the valley sides towards the River Tame.
Drain	Set from an elevation of 85mAOD to an elevation of 76mAOD with a conductance of 50m^2/day	The River Tame has been digitised as a fully draining drain boundary. The elevations of the River Tame were assigned from Environment Agency river bed level data.
Eastern boundary constant head	Set at 1m below the ground surface	The eastern boundary of the model has been set as a constant head boundary 1mBGL based off of model calibration and from the available water strike data from BGS boreholes.
Northern boundary constant head	Set at 3m below the ground surface	The western boundary of the model has been set as a constant head boundary 3mBGL based off of model calibration and from the available water strike data from BGS boreholes.
Southern boundary constant head	Set at 3m below the ground surface	The southern boundary of the model has been set as a constant head boundary 3mBGL based off of model calibration and from the available water strike data from BGS boreholes.

Boundary type	Boundary condition	Justification
Recharge	Set as 65mm/year over the full extent of layer 1	A recharge value of 65mm/year (approximately 20% of estimated effective annual rainfall) was applied to the entire model domain within the superficial deposits.

Material properties

4.4.9 The hydraulic conductivities used in the final model run are shown in Table 8.

Table 8: Bromford tunnel west portal model material properties

Unit	Designation	Hydraulic conductivity (m/s)	Source
Alluvium	Zone 2:	Kx = 1x10-4 Ky = 1x10-4 Kz = 1x10-4	Estimate based on typical literature values – then calibrated
River Terrace deposits	Zone 1:	Kx = 5x10-5 Ky = 5x10-5 Kz = 5x10-5	Estimate based on typical literature values – then calibrated
Mercia Mudstone	Zone 3:	Kx = 5x10-7 Ky = 5x10-7 Kz = 5x10-7	Estimate based on typical literature values – then calibrated

4.4.10 These values are a result of a significant amount of calibration and sensitivity testing. A wide range of conductivities were explored. For modelling purposes, it is assumed that these values represent the bulk hydraulic conductivity for each aquifer unit and are assigned to zones within the model layers representing these geological and hydrogeological units. For this model, hydraulic conductivity of each unit was assumed the same in each direction as the model was not sensitive to isotropy within the different zones.

4.4.11 The hydraulic conductivity values used in the Bromford tunnel west portal model are similar to the hydraulic conductivity values used in the Bromford tunnel eat portal model. The difference between each property in regards to hydraulic conductivity falls within half an order of magnitude.

4.4.12 No specific yield or storativity values are required in steady state analyses.

Model run settings

4.4.13 The model scenarios were all run in steady state, meaning that all boundary conditions remained constant and did not vary with time.

Simulation and stress period

4.4.14 It has been assumed that groundwater conditions are in steady state. The steady state simulation of groundwater flows has been carried out over a stress period of 1 year (365 days).

Solver

4.4.15 The solver used for the analysis was WHS.

Measurement units

4.4.16 The following measurement units are used throughout the simulations:

- length = metres (m);
- time = day (d);
- hydraulic conductivity = m/s;
- recharge = mm/yr; and
- calibration and sensitivity analysis.

4.4.17 Calibration of the model was achieved by means of a systematic adjustment of model properties and boundary conditions to achieve the best fit with observation points and the conceptual understanding of groundwater heads and flows. The baseline model calibration statistics for the 16 observation points with water level data are summarised in Table 9. These show a good calibration with the mean deviation from the observed water level data of 0.32m.

Table 9: Bromford tunnel west portal model statistics from final calibration

Maximum residual (m)	**Minimum residual (m)**	**Residual mean (m)**	**Absolute residual mean (m)**	**Standard error of the estimate (m)**	**Root mean squared (m)**	**Normalized root mean squared (%)**	**Correlation coefficient**
2.791 at SP18NW521	-0.116 at SP18NW502	-0.32	1.212	0.365	1.449	23.757	0.575

5 Model scenarios and results

5.1.1 Three scenarios have been modelled for each portal:

- baseline model – (i) to simulate the existing conditions before the construction of the Bromford tunnel (pre-construction); and
- predictive model – (ii) to simulate the effect of the cut and fill tunnels and the tunnel portals on the groundwater flow regime (post-development) and (iii) initial assessment of groundwater control (interceptor drain) option on groundwater levels and flows.

5.2 Bromford tunnel east portal

Baseline model (pre-development)

5.2.2 The simulated groundwater levels for the baseline model are shown in Figure 18 and Figure 19.

Figure 18: Bromford tunnel east portal model – baseline groundwater levels and flows

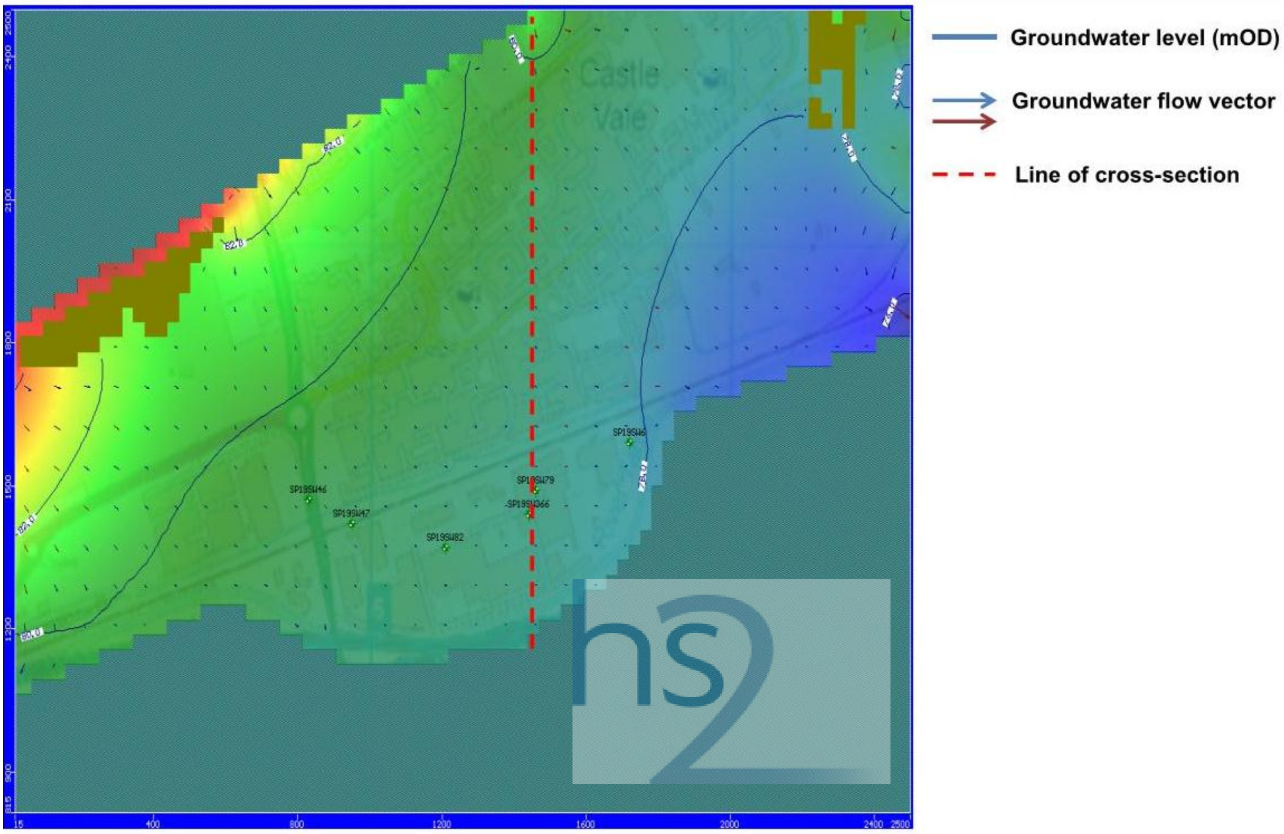
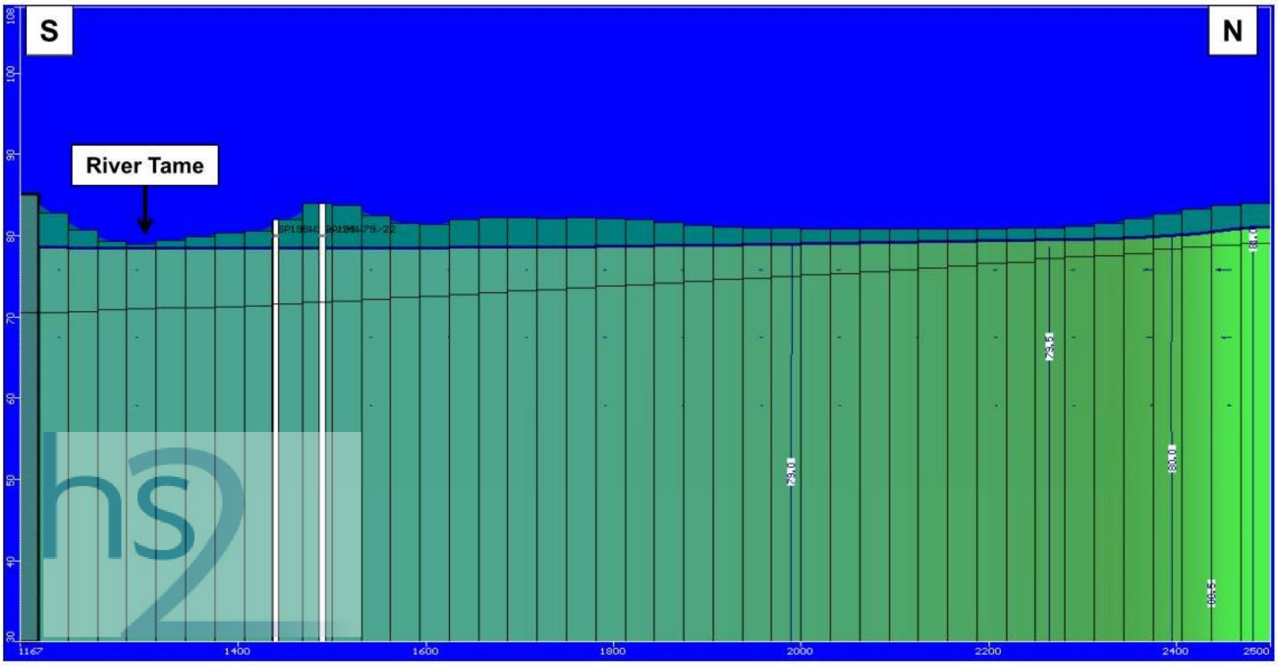


Figure 19: Bromford tunnel east portal model – baseline groundwater levels and flows (cross-section)



5.2.3 Groundwater flow is from the northern valley side south east towards the River Tame, simulated groundwater levels are from 84mOD to 76mOD. The cross-section in the vicinity of the Bromford tunnel east portal shows simulated groundwater levels are approximately 2 – 3m below ground level, which is consistent with the conceptual model.

5.2.4 Within the baseline model there are some limited areas of dry cells, which when dry will not let recharge through. These are located near the northern model boundary and away from the area of interest and not expected to interfere with the core model simulation.

Simulation Bromford tunnel east approach and portals (post-development)

5.2.5 From the Proposed Scheme drawings, shown in Volume 5: Map book CT-06, the tunnel portals and 'cut and fill' tunnels have been inserted into the baseline model as a 750m long "wall" boundary therefore representing an impermeable boundary within Layer 1 the superficial deposits.

5.2.6 The simulated groundwater levels and flow contours with the baseline model including the portal as a barrier are shown as Figure 20 and Figure 21, and the change in groundwater levels (drawdown or ponding) from the baseline in Figure 22. Running the model with the simulated tunnel shows that the 'cut and fill' tunnels and tunnel portals are having an effect on groundwater heads and flows. The tunnel is perpendicular to groundwater flow and they are creating a barrier to flow. The tunnel portal intercepts flow from the north and the model simulates additional ponding on the northern side of the portal of up to 0.7m. Drawdown on the southern side is simulated as 0.3m.

Figure 20: Bromford tunnel east portal model – baseline groundwater levels and flows with barrier

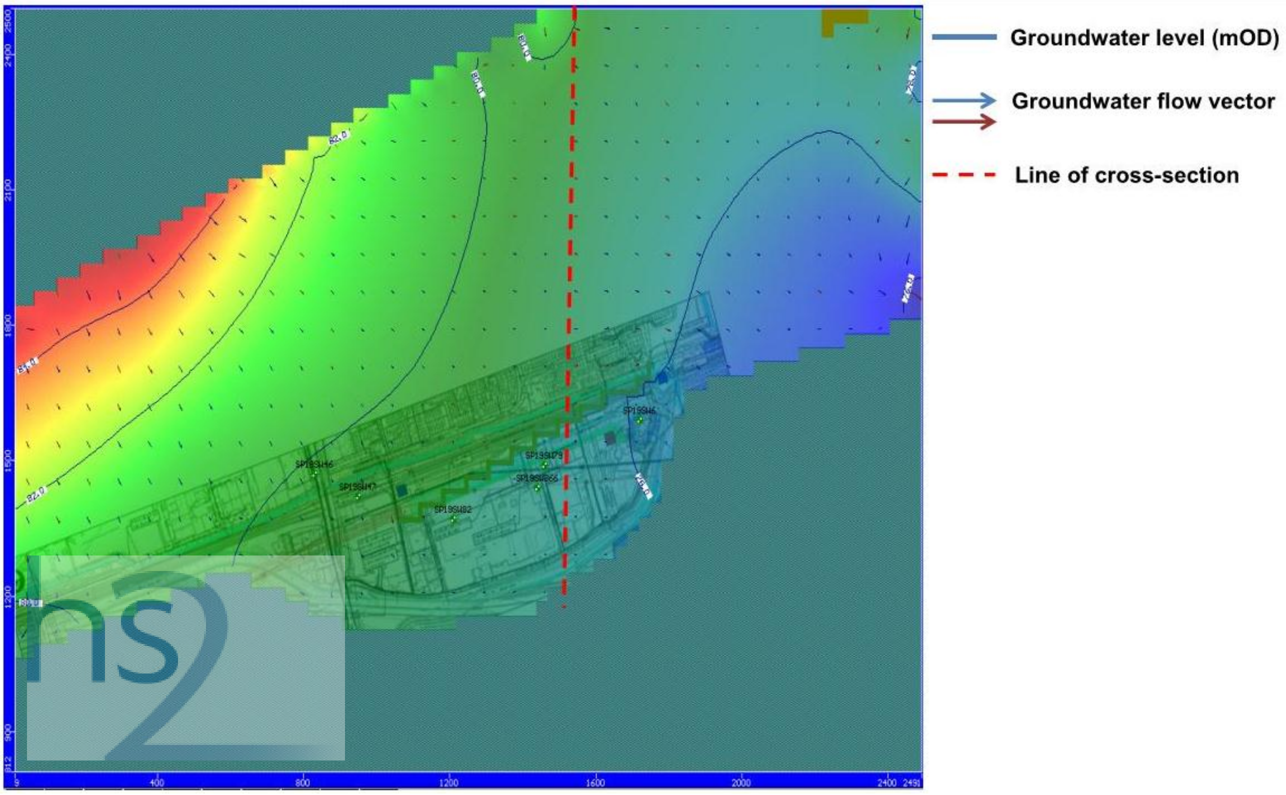


Figure 21: Bromford tunnel east portal model – baseline groundwater levels and flow with barrier (cross-section)

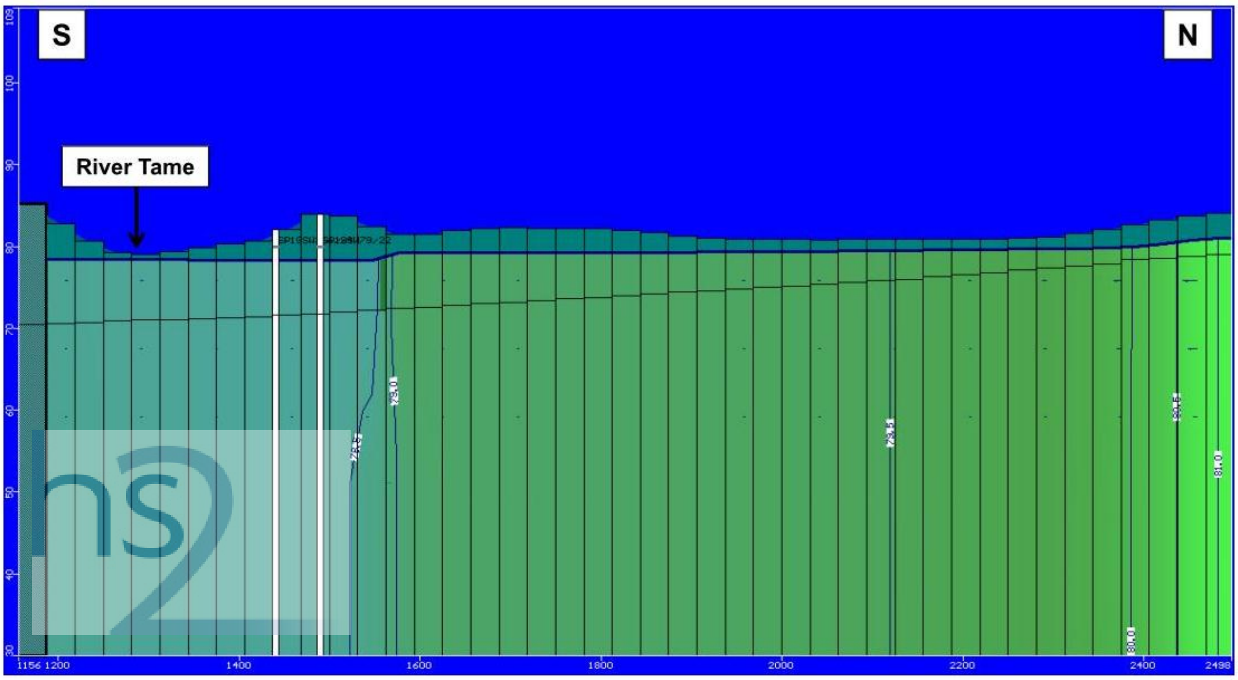
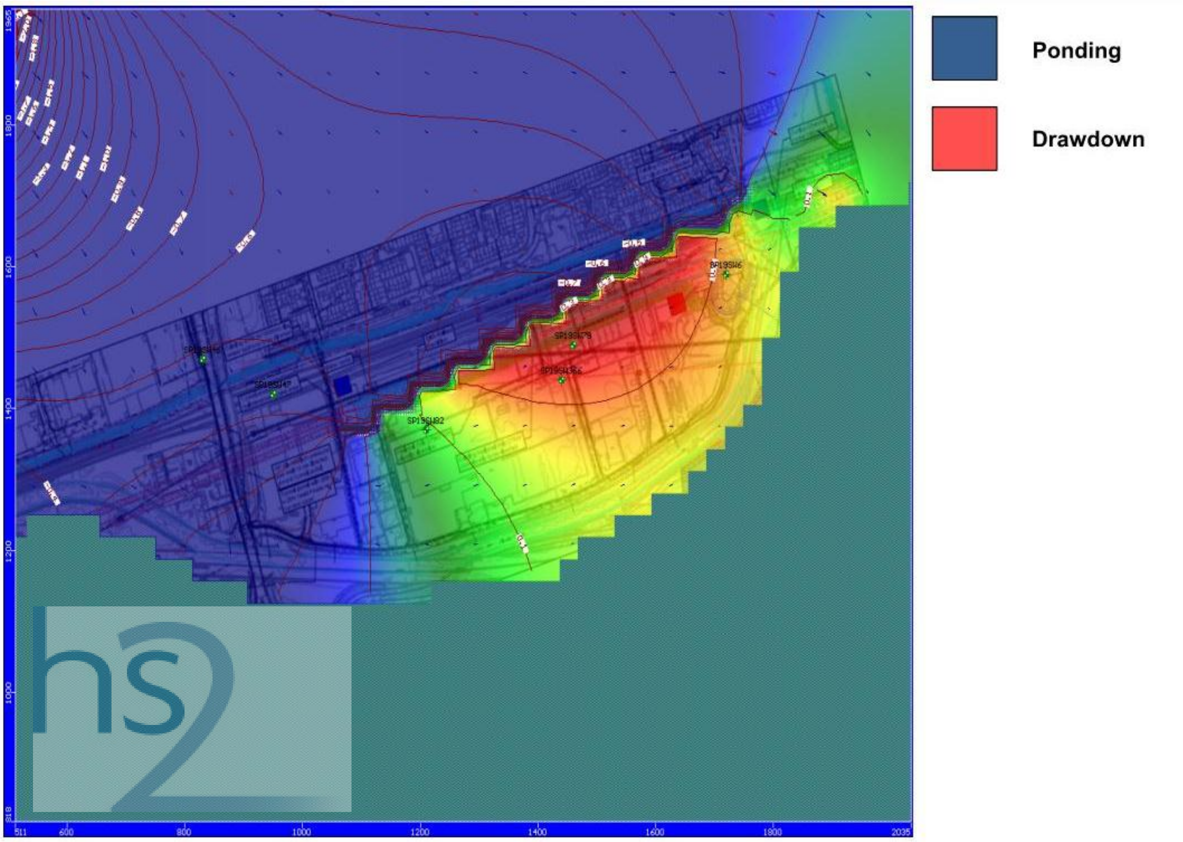


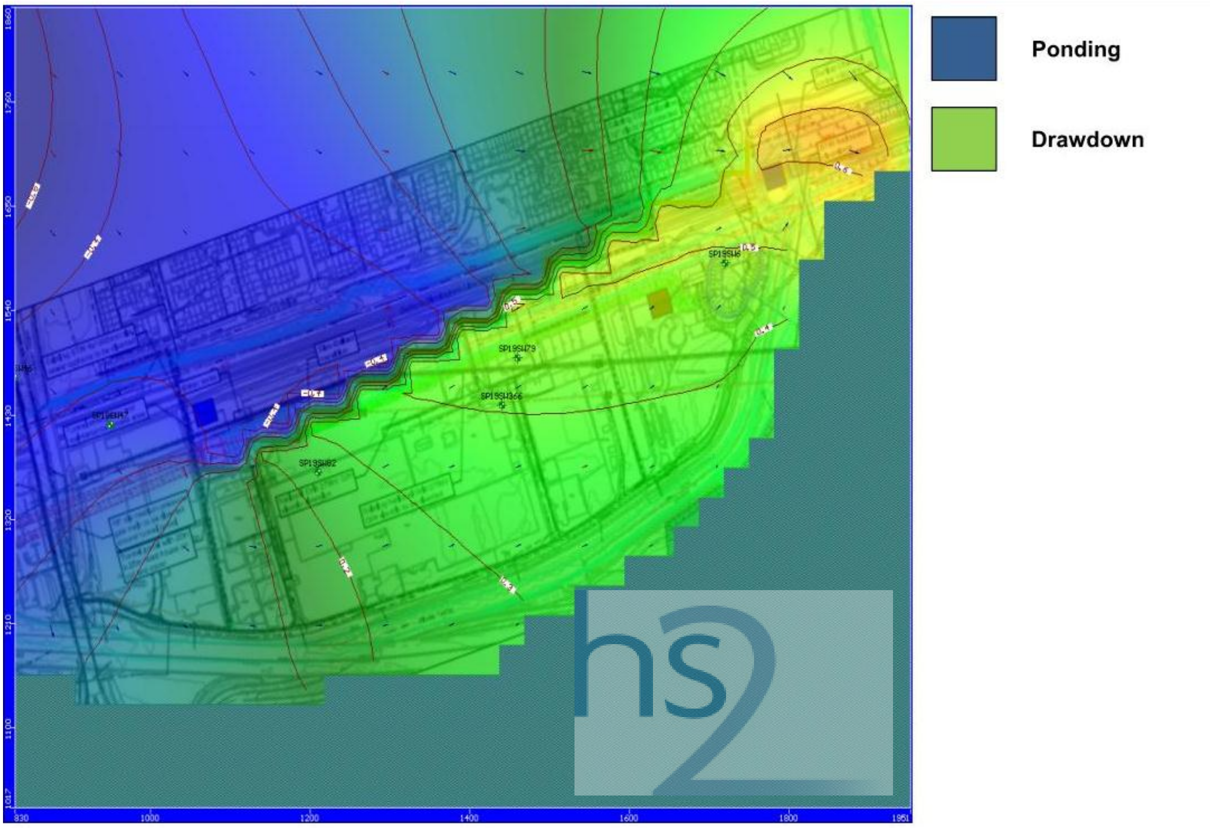
Figure 22: Bromford tunnel east portal model – change in groundwater levels (m)



5.2.7 The extent of groundwater levels within 1m of the ground surface is expected to increase on the northern side of the tunnel.

5.2.8 With an anticipated increase in groundwater levels on the northern side of Bromford tunnel east portal, the model was used to simulate the potential effect of introducing an interceptor drain on the northern boundary which drained down to the River Tame. The results of this model run are presented as Figure 23. The drain decreases drawdown on the northern side from 0.7m to 0.4m. The water balance for the drain indicates a potential daily inflow of approximately 700m^3/day.

Figure 23: Bromford tunnel east portal model – baseline with barrier and interceptor drain, change in groundwater level (m)



5.3 Bromford tunnel west portal

Baseline model (pre-development)

5.3.2 The simulated groundwater levels for the baseline model are shown in Figure 24 and Figure 25.

Figure 24: Bromford tunnel west portal model – baseline groundwater levels and flows

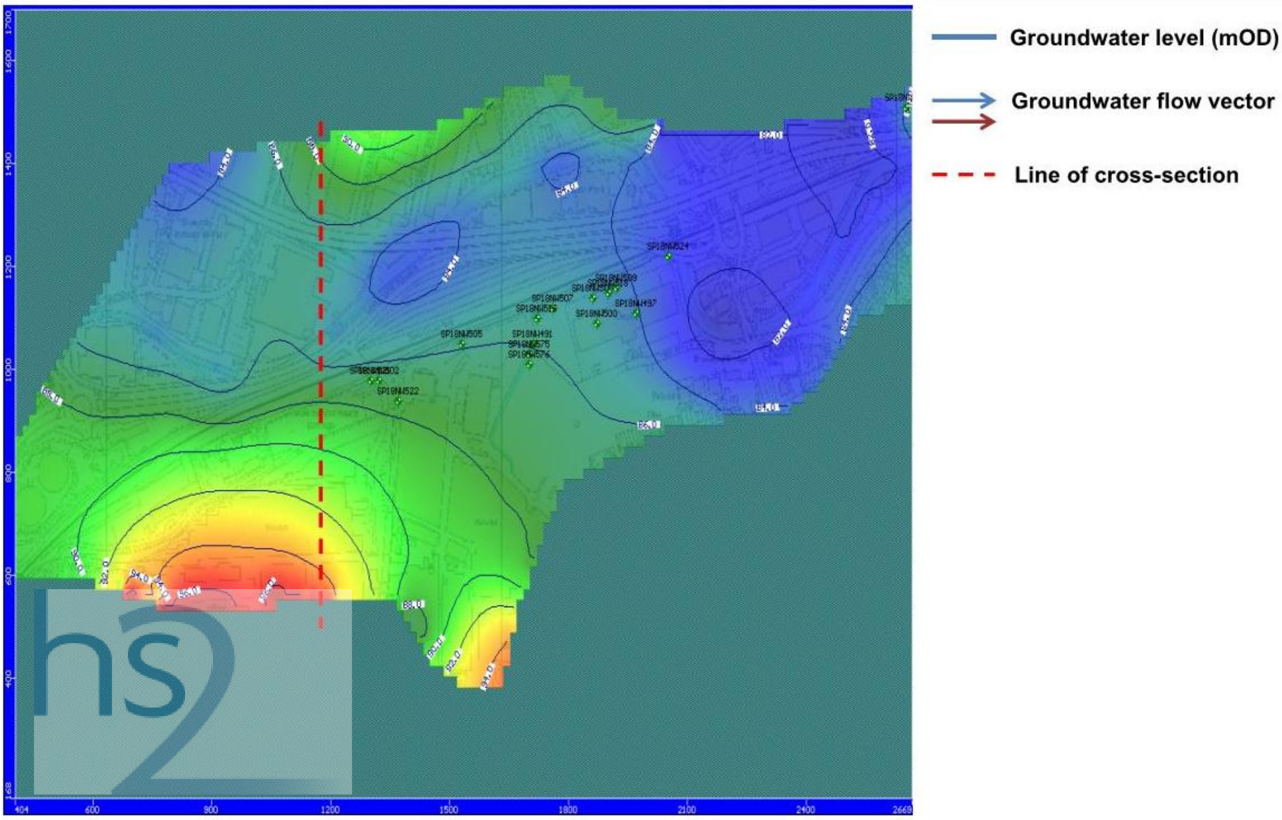
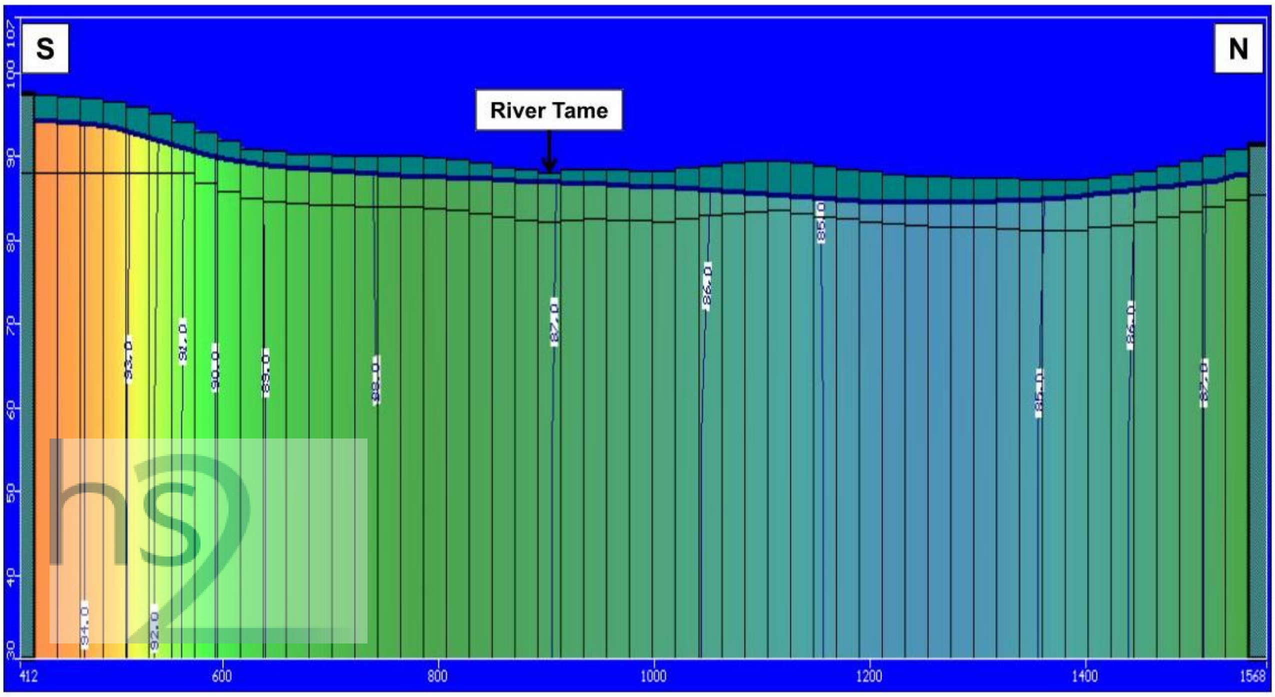


Figure 25: Bromford tunnel west portal model – baseline groundwater levels and flows (cross-section)



5.3.3 Groundwater flow is from the valley sides in the north and south towards and along the River Tame valley, with more flow from the south in the area of the Washwood Heath Brook. The cross-section in the vicinity of the Western Portal shows simulated groundwater levels are 2 – 5m below ground level, which is consistent with the conceptual model.

5.3.4 Within the baseline model for the Bromford tunnel west portal there are no areas of dry cells.

Simulation Bromford tunnel west approach and portals (post-development)

5.3.5 From Proposed Scheme drawings are shown in Volume 2: Map book CT-06, the Bromford tunnel west portal and 'cut and fill' tunnels have been inserted into the baseline model as a 1.4km long "wall" boundary therefore representing an impermeable boundary within Layer 1 the superficial deposits.

5.3.6 The simulated groundwater levels and flow contours with the baseline model including the portal as a barrier are shown as Figure 26 and Figure 27, and the change in groundwater levels (drawdown or ponding) from the baseline in Figure 28. Running the model with the simulated tunnel shows that the 'cut and fill' tunnels and tunnel portals are having an effect on groundwater heads and flows. The tunnel is perpendicular to groundwater flow towards the River Tame and they are creating a barrier to flow. The tunnel portal intercepts flow particularly from the south and the model simulates additional ponding on the southern side of the portal of up to 2m. Drawdown on the northern side is simulated as up to 2m.

Figure 26: Bromford tunnel west portal model – baseline groundwater levels and flow with barrier

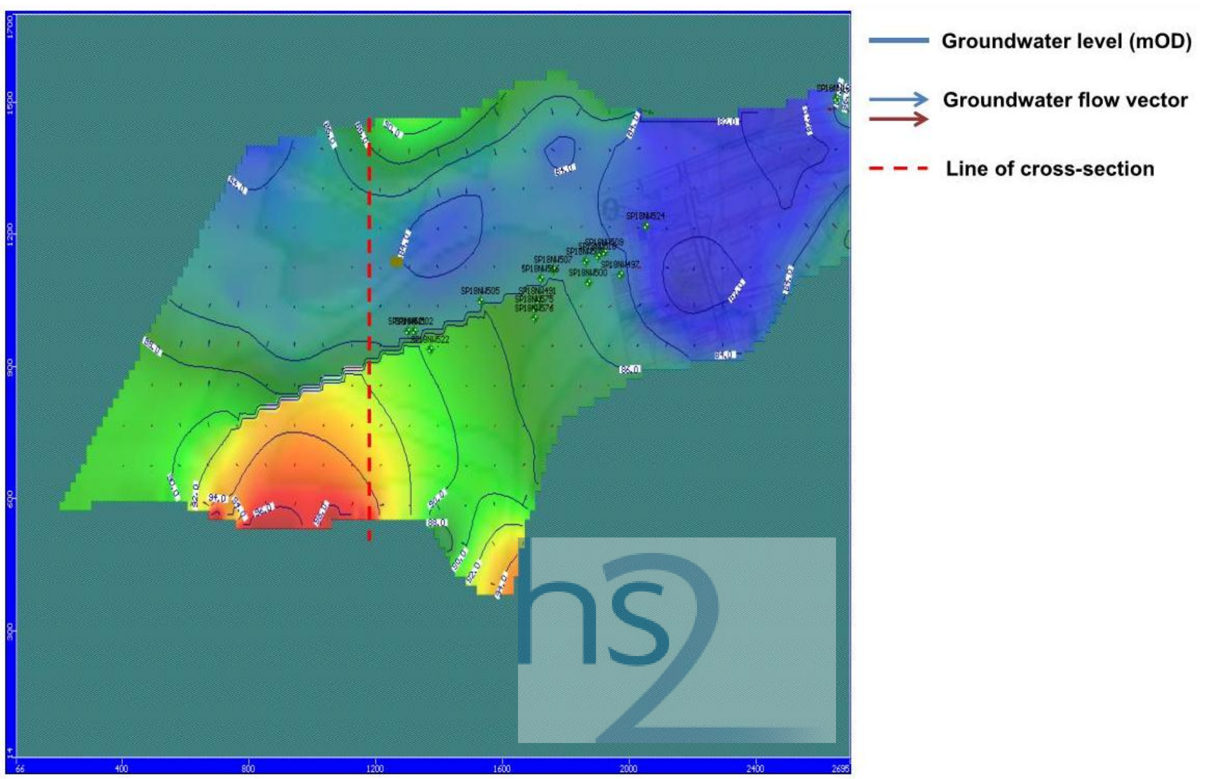


Figure 27: Bromford tunnel west portal model – baseline groundwater levels and flows with barrier (cross-section)

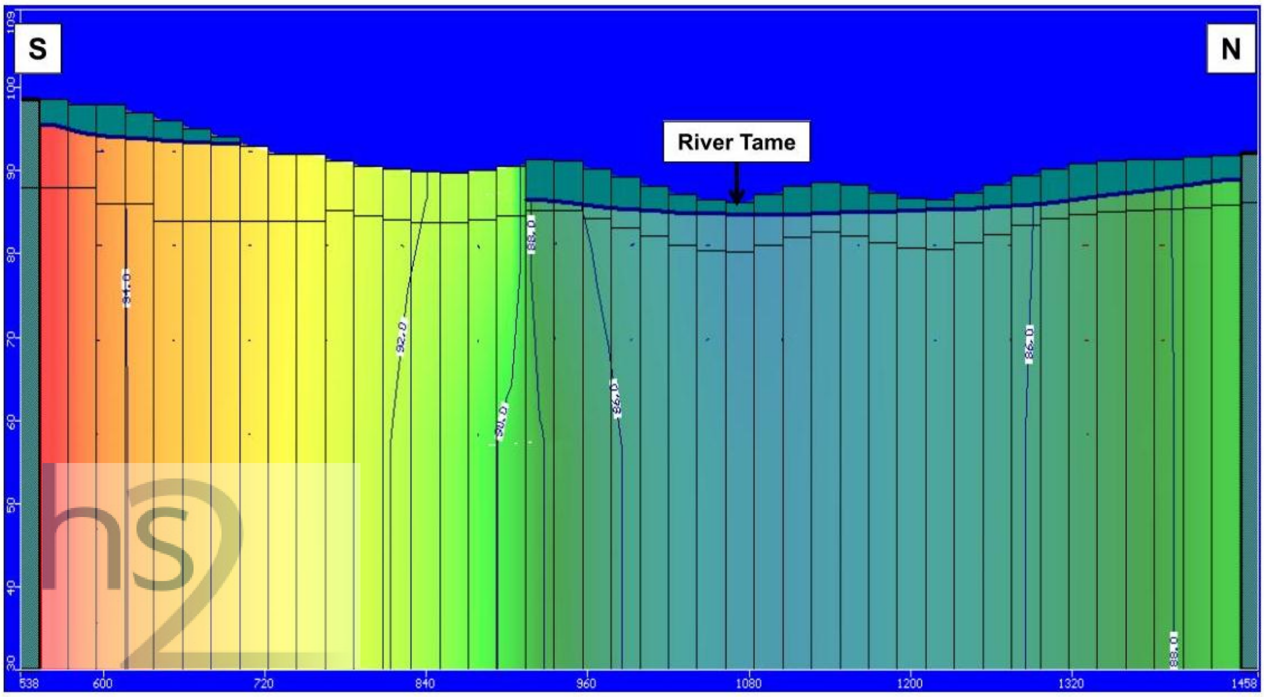
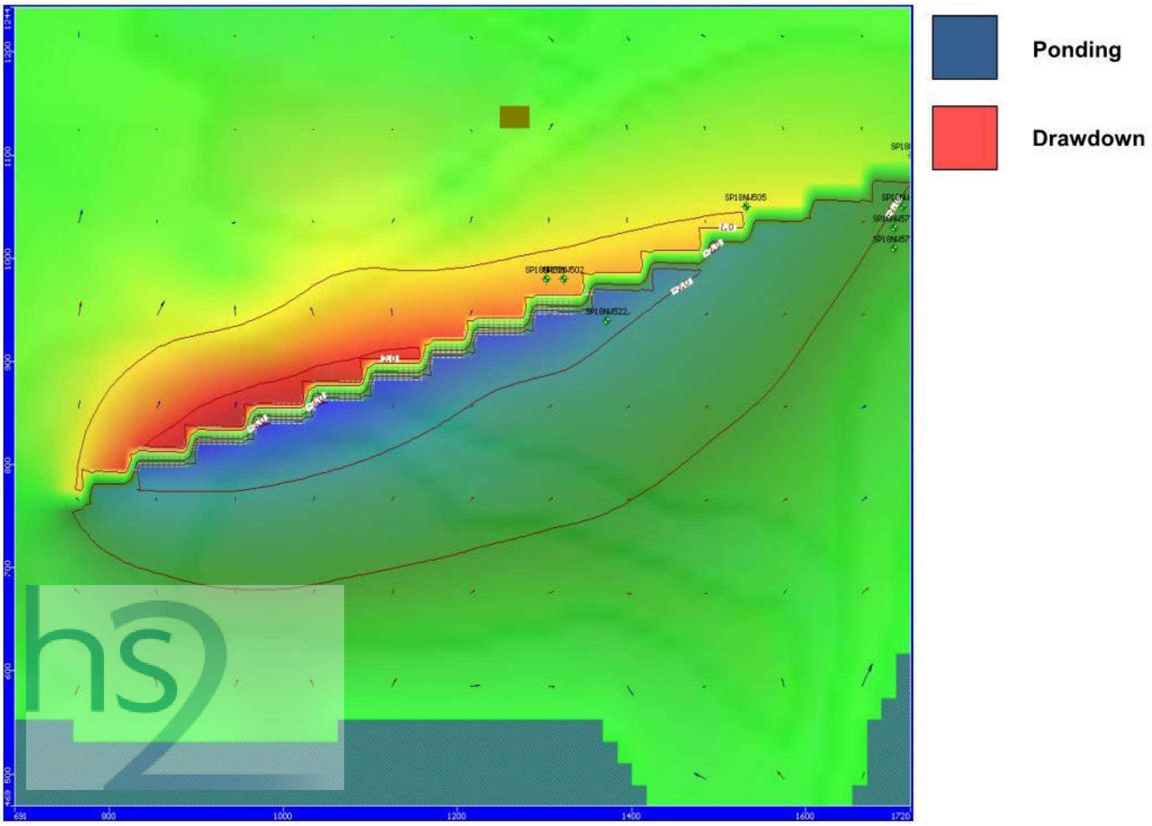


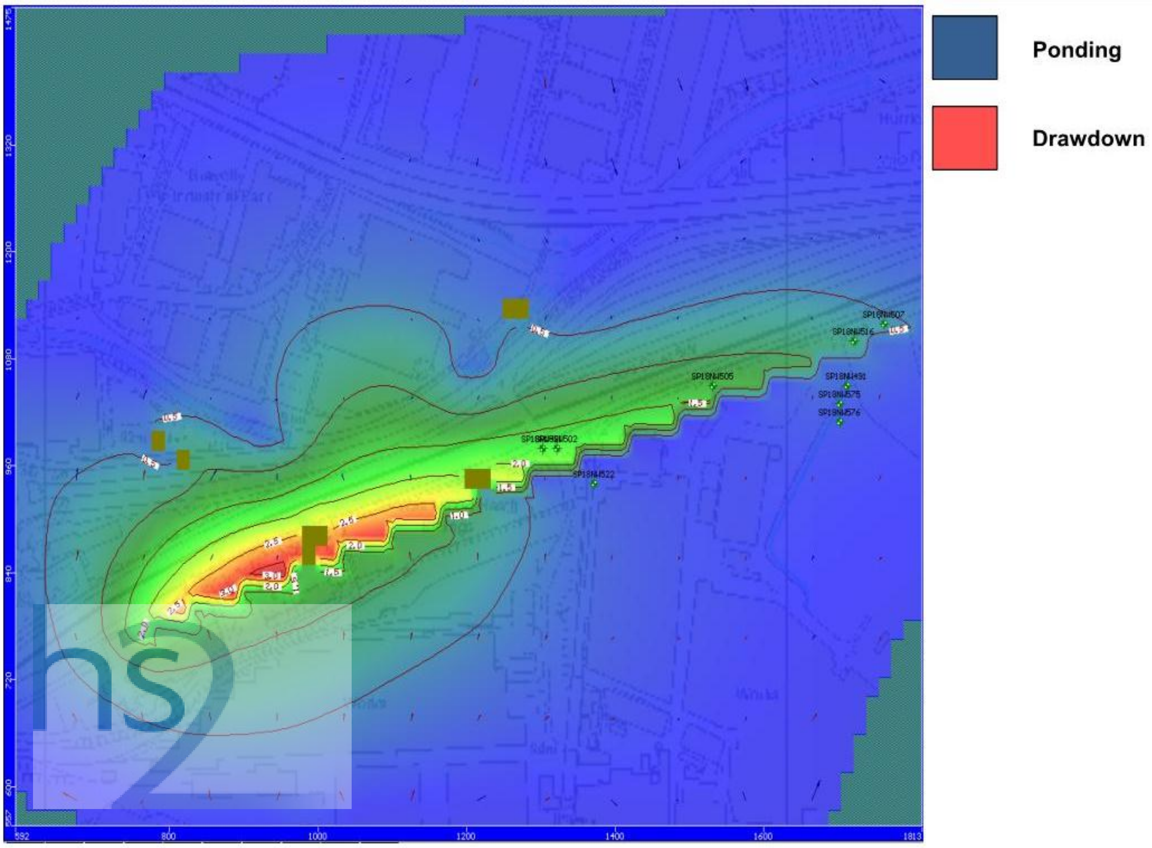
Figure 28: Bromford tunnel west portal model – change in groundwater levels (m)



5.3.7 The extent of groundwater levels within 1m of the ground surface is expected to increase on the southern side of the tunnel with minimal change in the rest of the model area.

5.3.8 With an anticipated increase in groundwater levels on the southern side of the Western Portal, the model was used to simulate the potential effect of introducing an interceptor drain on the southern boundary which drained down to the River Tame. The results of this model run are presented as Figure 29. The drain limits any additional ponding, although does increase the drawdown on the northern side of the portal by up to 3m. The water balance for the drain indicates a potential daily inflow of approximately 450m^3/day.

Figure 29: Bromford tunnel west portal model – baseline with barrier and interceptor drain, change in groundwater level (m)



6 Conclusions and recommendations

6.1 Conclusions

6.1.1 A conceptual hydrogeological model of the Tame Valley has been developed and used as the basis for development of an initial 3D groundwater model, constructed for each of the Bromford tunnel east and west portals and approach. The conceptual model has some important data limitations, particularly detailed understanding of actual groundwater levels and flows, since the available data is based largely on historical borehole log strike data which covers a wide time range not necessarily representative of current conditions. The spatial coverage is also generally focused on the development area within the central valley. The other significant limitation is that no actual site specific aquifer property information has been collected; assumptions are based on lithological descriptions within borehole logs.

6.1.2 However, the general conceptual understanding of groundwater levels and flow have been used to build and calibrate a baseline 3D groundwater model for each of the Bromford tunnel east and west portals which represent the assumed conceptual understanding.

6.1.3 The baseline models were then used to simulate the potential impacts of the tunnel approach on groundwater levels and flows. The model shows that construction of the tunnel portals through the water bearing superficial deposits is expected to intercept and divert groundwater flow paths.

6.1.4 The model predicts the Bromford tunnel west portal approach will have the greatest impact with a simulated ponding of groundwater on the southern boundary of 2m and a drawdown of groundwater on the northern side of 2m. This is in an area where water strike information indicates existing groundwater levels are between 2 and 5 m depth. The eastern tunnel approach shows less of an impact, with a predicted ponding of up to 0.7m on the northern side and drawdown of up to 0.4m on the southern side. This is in an area where water strike information indicates existing groundwater levels are between 2 to 3m depth.

6.1.5 The increased drawdown effect on groundwater levels may have an effect on river flows where the Tame is in continuity with groundwater. This issue requires more detailed understanding of the local groundwater-surface water interaction, effect of control and drainage structures as well as confidence on actual groundwater levels.

6.1.6 The model was used to assess the potential effect of interceptor drainage to control groundwater levels and the likely inflows quantified. The initial modelling results indicate that this could be a feasible option to control groundwater levels but does require more detailed assessment to develop the design option including the environmental and regulatory considerations.

6.2 Recommendations

6.2.1 The initial groundwater modelling has indicated that there is the potential for the Bromford tunnel east and west portals to act as a barrier to groundwater through flow within the superficial deposits. However, it is recognised that the conceptual model and initial groundwater model are based on water strike data and that aquifer properties used are within the range of literature values but not proven on site.

6.2.2 It is recommended that these important uncertainties are investigated as part of the on-going design process to refine the conceptual and numerical model build properties. To mitigate this gap in understanding it is recommended that a detailed review and collection of local site investigation data is undertaken to confirm the understanding of groundwater conditions, flow direction and aquifer properties.

6.2.3 Depending on the depth of groundwater proven from site investigation, the potential increase / drawdown on groundwater levels may result in a long term shallow groundwater level condition in areas adjacent to the portals. It is recommended that an feasibility options for groundwater control is developed taking account of the existing drainage system and controls. These include the use of passive drainage as well as active pumping measures.

7 References

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